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META 2021 Warsaw - Poland
The 11th International Conference on Metamaterials, Photonic Crystals and Plasmonics

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META 2021 gratefully acknowledges the support of these institutions and companies for their contribution to the success of this conference.
Robert W. Boyd

University of Ottawa, Canada and University of Rochester, USA

How Light Behaves when the Refractive Index Vanishes

Robert Boyd received the B.S. degree in physics from the Massachusetts Institute of Technology and the Ph.D. degree in physics in 1977 from the University of California at Berkeley. His Ph.D. thesis was supervised by Charles Townes and involved the use of nonlinear optical techniques in infrared detection for astronomy. Professor Boyd joined the faculty of the Institute of Optics of the University of Rochester in 1977 and in July 2001 he became the M. Parker Givens Professor of Optics. In 2010, he became Professor of Physics and Canada Excellence Research Chair in Quantum Nonlinear Optics at the University of Ottawa. His research interests include studies of nonlinear optical interactions, studies of the nonlinear optical properties of materials, the development of photonic devices including photonic biosensors, and studies of the quantum statistical properties of nonlinear optical interactions. Professor Boyd has written two books, co-edited two anthologies, published over 200 research papers, and has been awarded five patents. He is a fellow of the Optical Society of America and of the American Physical Society and is the past chair of the Division of Laser Science of the American Physical Society.

Federico Capasso

Harvard University, USA

Structuring Light and Dark with Metaoptics

Federico Capasso is the Robert Wallace Professor of Applied Physics at Harvard University, which he joined in 2003 after 27 years at Bell Labs where he was Member of Technical Staff, Department Head and Vice President for Physical Research. He is visiting professor at NTU with both the School of Physical and Mathematical Sciences and Electrical and Electronic Engineering. His research has focused on nanoscale science and technology encompassing a broad range of topics. He pioneered band-structure engineering of semiconductor nanostructures and devices, invented and first demonstrated the quantum cascade laser and investigated QED forces including the first measurement of a repulsive Casimir force. His most recent contributions are new plasmonic devices and flat optics based on metasurfaces. He is a member of the National Academy of Sciences, the National Academy of Engineering, the American Academy of Arts and Sciences. His awards include the King Faisal Prize, the IEEE Edison Medal, the SPIE Gold Medal, the American Physical Society Arthur Schawlow Prize in Laser Science, the Jan Czochralski Award for lifetime achievements in Materials Science, the IEEE Sarnoff Award in Electronics, the Materials Research Society Medal, the Wetherill Medal of the Franklin Institute, the Rank Prize in Optoelectronics, the Optical Society Wood Prize, the Berthold Leibinger Future Prize, the Julius Springer Prize in Applied Physics, the European Physical Society Quantum Electronics Prize.
Nader Engheta  
*University of Pennsylvania, USA*

**4D Structured Waves**

Nader Engheta is the H. Nedwill Ramsey Professor at the University of Pennsylvania in Philadelphia, with affiliations in the Departments of Electrical and Systems Engineering, Materials Science and Engineering, Physics and Astronomy, and Bioengineering. He received his B.S. degree from the University of Tehran, and his M.S and Ph.D. degrees from Caltech. His current research activities span a broad range of areas including nanophotonics, metamaterials, nano-scale optics, graphene optics, optical metatronics, imaging and sensing inspired by eyes of animal species, optical nanoengineering, microwave and optical devices, and physics and engineering of fields and waves. He has received several awards for his research including the 2017 William Streifer Scientific Achievement Award from the IEEE Photonics Society, the 2015 Gold Medal from SPIE, the 2015 Fellow of US National Academy of Inventors (NAI), the 2015 National Security Science and Engineering Faculty Fellow (NSSEFF) Award (also known as Vannevar Bush Faculty Fellow Award) from US Department of Defense, the 2015 IEEE Antennas and Propagation Society Distinguished Achievement Award, the 2015 Wheatstone Lecture in King’s College London, the 2014 Balthasar van der Pol Gold Medal from the International Union of Radio Science (URSI), the 2013 Inaugural SINA Award in Engineering, the 2012 IEEE Electromagnetics Award, 2006 Scientific American Magazine 50 Leaders in Science and Technology, the Guggenheim Fellowship, and the IEEE Third Millennium Medal. He is a Fellow of seven international scientific and technical societies, i.e., IEEE, URSI, OSA, APS, MRS, SPIE, and American Association for the Advancement of Science (AAAS). He has received the honorary doctoral degrees from the Aalto University in Finland in 2016 and from the University of Stuttgart, Germany in 2016.

Maiken H. Mikkelsen  
*Duke University, USA*

**Applications of metasurfaces: From multispectral imaging to optical communications and biosensing**

Maiken H. Mikkelsen is the James N. and Elizabeth H. Barton Associate Professor at Duke University in the Department of Electrical and Computer Engineering, and by courtesy, in the Departments of Physics and Mechanical Engineering and Materials Science. She received her B.S. in Physics from the University of Copenhagen in 2004, her Ph.D. in Physics from the University of California, Santa Barbara in 2009 and was a postdoctoral fellow at the University of California, Berkeley before joining Duke University in 2012. Her research explores nanophotonics and new quantum materials to enable transformative breakthroughs for optoelectronics, quantum science, the environment and human health. Her awards include the Maria Goeppert Mayer Award from the American Physical Society, the NSF CAREER award, the Moore Inventor Fellow award from the Gordon and Betty Moore Foundation, Young Investigator Program Awards from the Office of Naval Research, the Army Research Office and the Air Force Office of Scientific Research, the Cottrell Scholar Award from the Research Corporation for Science Advancement, and the Early Career Achievement Award from SPIE – the International Society for Optics and Photonics.
Masaya Notomi  
NTT Basic Research Labs., Japan

Integrated Nanophotonics for Optoelectronic Computation

Masaya Notomi received his B.E., M.E. and Ph.D. degrees in applied physics from The University of Tokyo, Japan in 1986, 1988, and 1997, respectively. He joined NTT Optoelectronics Laboratories, Nippon Telegraph and Telephone Corporation in 1988 and moved to NTT Basic Research Laboratories in 1999. Since then, his research interest has been to control the optical properties of materials and devices by using artificial nanostructures, and engaged in research on quantum wires/dots and photonic crystal structures. In 1996-1997, he was a visiting researcher of Linkoping University, Sweden. He was a guest associate professor of Applied Electronics in 2003-2009 and is currently a guest professor of Physics in Tokyo Institute of Technology. He was appointed as Senior Distinguished Scientist of NTT since 2010. He is currently a director of NTT Nanophotonics Center. He received IEEE/LEOS Distinguished Lecturer Award in 2006, Japan Society for the Promotion of Science (JSPS) prize in 2009, Japan Academy Medal in 2009, the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology (Prize for Science and Technology, Research Category) in 2010, and IEEE Fellow grade in 2013. He served as a member of National University Corporation Evaluation Committee in the Japanese government. He is a research director of JST CREST program from 2015. He is also a member of the Japan Society of Applied Physics, APS, IEEE, and OSA.

Deirdre O’Carroll  
Rutgers University, USA

Metasurfaces for Light Management in Semiconductor Thin Films

Deirdre O’Carroll is an Associate Professor in the Departments of Materials Science, Engineering and Chemistry and Chemical Biology at Rutgers University. Her research areas include nanophotonics, plasmonics, organic optoelectronics and energy materials. She obtained her B.E. in Electrical Engineering in 2002, and a PhD in Microelectronics in 2008 at University College Cork and the Tyndall National Institute, Ireland. Prior to joining Rutgers in 2011, she conducted postdoctoral research in plasmonics at California Institute of Technology in the US and at the University of Strasbourg and CNRS in France. She is a recipient of a National Science Foundation CAREER Award (2016), an American Chemical Society Young Investigator Award in Polymer Material Science and Engineering (2017) and a Science Foundation Ireland Future Research Leaders Award (2018). She is an associate editor for the SPIE Journal of Photonics for Energy and a member of the editorial advisory board for APL Photonics.
Vladimir M. Shalaev
Purdue University, USA

Empowering Quantum Photonics with Nanoplasmonics and Machine Learning

Vladimir M. Shalaev, Scientific Director for Nanophotonics at Birck Nanotechnology Center and Distinguished Professor of Electrical and Computer Engineering at Purdue University, specializes in nanophotonics, plasmonics, and optical metamaterials. Vladimir M. Shalaev has received several awards for his research in the field of nanophotonics and metamaterials, including the Max Born Award of the Optical Society of America for his pioneering contributions to the field of optical metamaterials, the Willis E. Lamb Award for Laser Science and Quantum Optics, IEEE Photonics Society William Streifer Scientific Achievement Award, Rolf Landauer medal of the ETOPIM (Electrical, Transport and Optical Properties of Inhomogeneous Media) International Association, the UNESCO Medal for the development of nanosciences and nanotechnologies, OSA and SPIE Goodman Book Writing Award. He is a Fellow of the IEEE, APS, SPIE, MRS and OSA. Prof. Shalaev has authored three books, thirty invited book chapters and over 500 research publications.
KEYNOTE SPEAKERS

Ali Adibi  
*Georgia Institute of Technology, USA*

*Analysis and Knowledge Discovery of Metastructures Using Deep Learning and Machine Learning Approaches in Reduced-dimensionality Spaces*

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*Tunable and Time-Modulated Flat Optics*

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*A new spin for acoustics*

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*University of Illinois, USA*

*Volumetric microscale gradient refractive index lenses and waveguides for ultra-dense 3D optics*

Hyuck Choo  
*Samsung Electronics Co., Ltd., Korea*

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Javier García de Abajo  
*ICFO-Institut de Ciencies Fotoniques, Spain*

*Nanophotonics with Two-Dimensional Materials*

Hilmi Volkan Demir  
*Nanyang Technological University (NTU), Singapore*

*Semiconductor Nanocrystal Optoelectronics: Pushing the Limits*
Alexander Govorov  
*Ohio University, USA*

Optical and photochemical properties of chiral plasmonic nanostructures

Deep Jariwala  
*University of Pennsylvania, US*

Tunable Light-Matter Coupling in Low-Dimensional Excitonic Semiconductors

Mona Jarrahi  
*University of California Los Angeles, USA*

Wavelength conversion through plasmonic photoconductive nanostructures

Seokwoo Jeon  
*Korea Advanced Institute of Science and Technology, Korea*

Fast, Low Cost Fabrication of Optimized 3D Nanostructures for Energy Transfer and Transport Properties

Philippe Lalanne  
*Institut d’Optique Graduate School, France*

Rigorous modal analysis of micro and nanoresonators

Howard Lee  
*UC Irvine, USA*

Active Epsilon-near-zero Photonics

Hiromi Okamoto  
*Institute for Molecular Science, Japan*

Chiral Near-Field Properties of Plasmonic Nanomaterials: Imaging and Functions

Sir John B. Pendry  
*Imperial College London, UK*

Metamaterials that travel faster than light: putting the squeeze on photons
Junsuk Rho
Pohang University of Science and Technology (POSTECH), Korea
Dielectric metasurfaces for flat optics: wavefront engineering and future applications

Volker J. Sorger
George Washington University, USA
Strainoptronics: A New Degree of Freedom for 2D Material Device Engineering

Martin Wegener
KIT, Germany
3D Laser Nanoprinting of 3D Metamaterials

Rachel Won
Nature Photonics (United Kingdom)
3D Publishing in Nature Journals

Eli Yablonovitch
UC Berkeley, USA
The Challenge of META is (Aperiodic) Inverse Electromagnetic Design
META 2021 features several technical tutorials instructed by world-leading experts on various topics of interest to the META community. Tutorials are intended to provide a high quality learning experience to conference attendees. The tutorials address an audience with a varied range of interests and backgrounds: beginners, students, researchers, lecturers and representatives of companies, governments and funding agencies who wish to learn new concepts and technologies. The tutorials are part of the conference technical program, and are free of charge for the conference attendees.

Organizer

Prof. Ishwar Aggarwal, UNC Charlotte, USA

Tutorials & Instructors

Prof. Federico Capasso

Harvard University, USA

Tutorial I: Metasurface Flat Optics: from components to mass manufacturing to systems

Flat optics based on metasurfaces has emerged in recent years as a promising alternative to refractive and Fresnel optics in many applications, due to the smaller footprint, mass-manufacturing using the same technology of semiconductor chips, easier control of aberrations and multifunctionality. I will cover recent advances in components and show how they have led to breakthroughs in cameras and other systems such as ultra compact spectrometers.
Tutorial II : Design of Active and Reconfigurable Metasurfaces

A grand challenge for nanophotonics is the realization of comprehensively tunable metasurface nanoantenna arrays enabling dynamic, active control of the key constitutive properties of light – amplitude, phase, wavevector and polarization. Achieving this will open new photonics applications in phased-array optical beam steering, visible light modulation for communications and thermal radiation management. This tutorial will discuss design approaches for active and reconfigurable metasurfaces including selection of active materials, electromagnetic design and time-modulation. We will also survey status and outlook for electronically tunable and reconfigurable plasmonic and all-dielectric metasurfaces, whose elements are arbitrarily reprogrammable, enabling a wide array of functions, including steering, focusing, and frequency multiplexing of scattered radiation.

Tutorial III : Artificial Intelligence in Meta-optics

A survey of new artificial-intelligence-based approaches for analysis, design, optimization, and knowledge discovery in electromagnetic metastructures will be presented. Recent advances in using both deep learning and machine learning techniques, and their application to practical problems will be covered. These techniques will not only enable more efficient designs of the electromagnetic metastructures (e.g., photonic metasurfaces) but also provide valuable insight about the complex physics of light-matter interactions in such structures. Details of the training process for these algorithms as well as the challenges and limitations of these techniques for different classes of metastructures will be discussed. Knowledge discovery using these techniques includes the study of feasibility of a certain optical response from a given class of metastructures and comparing the roles of different design parameters to facilitate the inverse design process.
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Plenary Lectures
How Light Behaves when the Refractive Index Vanishes

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Abstract
We describe some of the properties of light propagation through material for which the dielectric permittivity and hence the refractive index is nearly vanishing. Among other unusual optical properties, we find that such epsilon-near-zero (ENZ) materials display an extremely large nonlinear optical response, with important implications for the field of photonics.

Summary
The propagation of light is profoundly modified for a material for which the dielectric permittivity epsilon is nearly vanishing. In such a situation, the refractive index also nearly vanishes, and thus both the wavelength of light and the phase velocity of light become nearly infinite. Radiative processes also are strongly modified, with both the Einstein $A$ and $B$ coefficients being dependent on the refractive index of the material. We have recently found that nonlinear optical properties tend to be strongly enhanced in epsilon-near-zero (ENZ) materials [1]. For the case of indium-tin-oxide (ITO), we measured a huge value (10^6 times larger than that of fused silica) of the nonlinear coefficient $n_2$. In subsequent work, we have fabricated a metasurface consisting of gold nanorods on an ITO substrate, and we have found that the nonlinear coefficient is further enhanced and can be controlled in both magnitude and sign [2]. The talk then turns to a discussion of the implications of the use of ENZ materials as a platform for applications in the field of nanophotonics.

Acknowledgements
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References
Empowering Quantum Photonics with Nanoplasmonics and Machine Learning

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New approaches to address major challenges in quantum photonics by employing powerful ideas and concepts developed in the field of plasmonic metamaterials will be discussed.
Structuring Light and Dark with Metaoptics

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Abstract

Metasurfaces can generate arbitrary vector beams. I will discuss devices that enable light’s spin and orbital angular momentum (OAM) to evolve, simultaneously, from one state to another along the propagation direction and polarizing elements that virtually rotate their orientation as a function of the propagation distance. Advances in high OAM lasing will be reported along with the design and realization of two-dimensional phase and polarization singularities.
Metasurfaces for Light Management in Semiconductor Thin Films

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Abstract

In thin-film optoelectronic devices, manipulation of light below the diffraction limit in a two-dimensional plane is necessary for efficient light utilization within the semiconductor active layer. Metasurfaces are emerging as promising materials for this purpose because of their extreme thinness and their ability to localize the electric field of light at their surface. In this talk, recent work on improving light trapping and light extraction in organic semiconductor thin films using plasmonic metasurfaces will be presented. Numerous optical phenomena, such as absorption induced scattering, out-of-plane waveguiding and morphology-dependent surface plasmon outcoupling, are identified due to exciton-plasmon coupling between the organic semiconductor and the metasurface. Interactions between localized and propagating surface plasmon polaritons and the excitonic transitions of a variety of semiconducting polymer materials will be discussed and ways in which these interactions may be optimized for particular optoelectronic applications will be presented.
Integrated Nanophotonics for Optoelectronic Computation

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Abstract

Recent strong demands for the computational power in AI applications are leading to a research renaissance of optical computations. One can perform computations at light speed in a chip, especially powerful for analog computation using linear optics. In order to make realistic computing machines, however, optical circuits should be tightly connected with electronic digital circuits with large memories, which is seriously hindered by energy-hungry optical-electrical and digital-analog conversions. In this talk, we show that integrated nanophotonics technologies enable energy-effective O/E and D/A conversions in an integrable fashion. In addition, it is essentially important to add integrable energy-efficient nonlinearities at appropriate places in linear-optic circuits. We present our recent results of such nonlinear elements based on OEO transistors and nanomaterial-loaded nanophotonics. Finally, we will discuss possible applications of these technologies for optoelectronics computations.
Applications of metasurfaces: From multispectral imaging to optical communications and biosensing

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Abstract

In this talk, I will present advances in plasmonic metasurfaces with examples of potential future applications in a wide-variety of areas from multispectral imaging to optical communications and biosensing.
4D Structured Waves

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Abstract

Varying materials parameters in time, in addition to (or instead of) spatial inhomogeneities in material platforms, can provide additional degrees of freedom in structuring and sculpting waves that lead to interesting functionalities in wave-matter interaction. While the spatial and/or temporal variations of material parameters have certain analogies and similarities, they exhibit important differences. In this talk, I will present an overview of some of the ongoing research programs on this topic in my group, will discuss the salient features, and will forecast possible future directions.
Keynote Lectures
Dielectric metasurfaces for flat optics: wavefront engineering and future applications

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Miniaturization is a main stream in modern technology, but reduction of conventional optical components accompanies performance degradation that limits the minimum feature size of optical devices. Metasurfaces that consist of ultrathin subwavelength antenna arrays can be a promising solution because metasurfaces provide an effective way of wavefront engineering without constraints on the device size\textsuperscript{1}. Electromagnetic responses of individual building blocks are determined by its geometric configurations, and many kinds of antennas have been explored to clarify the capability of metasurfaces; thereby, it has been verified that dielectric antennas can control amplitude\textsuperscript{2}, phase\textsuperscript{3}, and even both of them simultaneously\textsuperscript{4,5}.

The capability of wavefront engineering allows to realize versatile future applications such as holograms, lenses and color filters. Fundamental limitations of conventional holograms such as twin image and narrow viewing angle can be removed by metaholograms due to their sub-wavelength pixel size. Propagation phase of isotropic building blocks enables polarization-insensitive operation\textsuperscript{5} while geometric phase of anisotropic building blocks allows broadband operation of metaholograms\textsuperscript{6,7,3}. Moreover, a multicolor metahologram can be achieved by combining propagation phase and geometric phase\textsuperscript{8}. It is also possible to realize polarization independent broadband beam splitting\textsuperscript{10} and random point-cloud generation for 3D detection based on metaholograms\textsuperscript{11}. The same principle of antenna design can be applied to ultrathin light-focusing devices of metalenses\textsuperscript{12,13}. On the other hand, amplitude-control metasurfaces can realize sub-wavelength color printing. Metasurfaces can have different colors by incident polarization enabling cryptographic applications\textsuperscript{2,14}. Comprehensive metasurfaces that enable to control both phase and amplitude have been realized by adjusting unit structures. The hologram resolution can be drastically improved by controlling complex amplitude using X-shaped antennas\textsuperscript{4}, and both functions of holography and color printing can be integrated in a single metasurface\textsuperscript{5}.

Recently, much metasurface research has aimed to embed nanoparticle-based hierarchy in building blocks to enhance the chirality\textsuperscript{15} and refractive index\textsuperscript{13,16}. In the future, metasurface research will be expanded to a practical region incorporating with large-scale fabrication\textsuperscript{13,16}.

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Rigorous modal analysis of micro and nanoresonators

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Microcavities and nanoresonators are characterized by their modes, called quasinormal modes because they are the eigensolutions of non-Hermitian operators. In contrast to waveguide and free space modes, quasinormal modes are not well documented in the literature, although nanoresonances play an essential role in current developments in nanophotonics. The reason is due to mathematical difficulties, see details in the recent review article [1], and especially to the fact that quasinormal modes cannot be normalized by their energy.

Complex mode Volume. The concept of complex V’s [Phys. Rev. Lett 110, 237401 (2013)] may appears as a mathematical abstraction. It is however rooted in important phenomena of resonant light-matter interactions and quantifies the non-Hermitian character of the interaction [1]. For instance, the ratio Im(V)/Re(V) provides an asymmetry into the mode contribution to the LDOS spectrum [2]. For strong coupling, it modifies the usual expression of the Rabi frequency by blurring and moving the boundary between the weak and strong coupling regimes.

Helped by cavity perturbation theory, see related earlier work in [2], and near field experimental data, we clarify the physics captured by the imaginary part of V and show how the real and imaginary parts can be directly measured with near-field microscopy.

Quasinormal mode expansion. The modal theory of optical resonators has recently achieved very important improvements, to such an extent that we may expect that future works will mostly consist in refinements rather than on fundamental developments. At the conference, we will show state of the art reconstruction of the field scattered by resonators in their quasinormal mode basis [4].

References:


The Challenge of META is (Aperiodic) Inverse Electromagnetic Design

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Abstract

Meta-Materials were inspired by the idea of periodic sub-wavelength geometrical units that produce an effective permittivity and permeability. Inevitably, in human affairs, there is a goal, and it may be that the goal is best achieved by an aperiodic rather than a periodic design. This is a universal problem in electromagnetics: What is the best design to achieve a specific goal?

The problem is exacerbated by the reality that any geometrical design could have millions of design parameters that define a desirable shape. With a particular goal in mind, the adjustment of any one design parameter, requires a revision of all the other parameters, making it hard, or impossible to converge on a good design. Essentially this is a problem in multi-variable calculus: How to co-optimize the millions of parameters that are implicit in any geometrical shape?

Fortunately, there are elegant mathematical methods that have emerged in recent years that permit the co-optimization of millions of variables but requiring only two solutions of Maxwell’s Equations. The mathematical approach is called the “Adjoint Method”, and it relies on the chain rule of calculus. Indeed this method has been rediscovered numerous times in the past 70 years, wherever some optimization over many variables is needed. This has many names. For example, in neural networks this is called “Back-Propagation”, but it is also used in Control Theory, mechanical design, etc.

One of the first electromagnetic applications of the “Adjoint Method” was toward the design of lithographic masks for the photographic process by which electronic chips are manufactured. These masks consist of thin-film Chromium on glass, intricately patterned, to photographically project out the exact shapes of transistors, wires, and other components on an integrated circuit. These metal film masks, so heavily used in electronics manufacturing, can be regarded as the original “meta-surface”.

Sub-wavelength transistor images were desired, but it was not at all clear what the mask pattern should be, that would produce those desired sub-wavelength images. The first company founded to employ the “Adjoint Method” for photo-lithography was Luminescent Inc., (2002). Luminescent introduced the slogan ILT “Inverse Lithography Technology” to be understood as a subset of Inverse Electromagnetic Design. Today, almost all memory chips and micro-processors use thin-film chromium masks and ILT software in their design and manufacture, meta-surfaces indeed.

Whether it’s a meta-lens or any other type of electromagnetic function, there is no need to slavishly follow the constraint of periodicity. Mathematical methods have been developed to efficiently optimize any type of electromagnetic function. I will provide the examples: “Silicon Photonics” couplers, optical antennas, solar cell surface textures, etc.
3D Laser Nanoprinting of 3D Metamaterials

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Abstract

We review our recent progress concerning 3D laser nanoprinting of 3D metamaterials. In the context of this special session, we emphasize advances in 3D additive manufacturing with respect to printing speed.

1. Introduction

When communicating results on 3D metamaterials \cite{1} to non-experts and laypersons, an ever re-occurring question is whether these architectures should be seen merely as toy “structures” or really as effective “materials”. Scientifically, using homogenization theory \cite{1}, this question can be answered for many (albeit not all) architectures in that a description in terms of an effective medium is justified. However, what many non-experts really mean is that the majority of 3D architectures has so few unit cells compared to what one is used to from ordinary atomic materials. On this basis, it seems difficult to imagine that 3D metamaterials will ever be good for anything in terms of applications.

2. Large-scale microstructured 3D metamaterials

3D laser nanoprinting allows for the making of nearly arbitrary complex 3D architectures \cite{2}. This form of 3D additive manufacturing is commonly based on multi-photon absorption of light. Reviews on this approach and many others can be found in \cite{2,3}.

3D additive manufacturing is based on assembling a small volume element, the 3D “voxel” (in analogy to the 2D picture element or “pixel”) into 3D architectures by adding more and more voxels during the fabrication process. Two decisive factors are the minimum accessible voxel size and the printing rate in terms of voxels/s \cite{2,3}. A recent benchmark example from our group \cite{3} is shown in Figure 1 \cite{3}.

Acknowledgements

I thank all of the members of my group as well as all the authors of Refs. \cite{1-3} for their contributions. This research has been funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany’s Excellence Strategy via the Excellence Cluster 3D Matter Made to Order (EXC-2082/1 – 390761711), by the Carl Zeiss Foundation through the “Carl-Zeiss-Foundation-Focus@HEiKA”, by the Helmholtz program “Science and Technology of Nanosystems” (STN) and the associated KIT project “Virtual Materials Design” (VIRTMAT), by the Karlsruhe School of Optics & Photonics (KSOP), by the Max Planck School of Photonics (MPSP), and by the KIT Nanostructure Service Laboratory (NSL).

References


Figure 1: Photograph of a 3D chiral mechanical metamaterial composed of 108000 cubic unit cells defined with sub-\textmu m precision by using rapid multi-focus two-photon-absorption based 3D laser nanoprinting \cite{3}. The total number of voxels exceeds 300 billion. The overall sample height is close to 1 cm. The individual 3D unit cells with a lattice constant of 80 \textmu m can barely be resolved with the naked eye. The shown image has been taken from Ref. \cite{3}.
Optical and photochemical properties of chiral plasmonic nanostructures

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Chiral photochemical reactions at the molecular level have proven to be a challenging task since chiral molecule species possess tiny chiroptical signals. In contrast, plasmonic nanocrystals offer very strong circular dichroism. We propose taking advantage of this property, introducing a novel mechanism driving surface photochemistry in a chiral plasmonic nanocrystal [1,2]. This mechanism is based on the generation of hot electrons and leads to plasmon-assisted chiral growth. The asymmetry factors for the chiral growth effects, driven by hot electrons, exceed the values observed in chiral molecular photophysics at least ten-fold.

References


Strainoptronics: A New Degree of Freedom for 2D Material Device Engineering

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Abstract Here we introduce ‘strainoptronics’ – the local strain engineering of 2D materials for novel optoelectronic components. We exemplary demonstrate heterogeneously integrating 2D materials in photonic circuits thus realizing a photodetector featuring a strong photosresponse (responsivity 0.5 A/W) operating at 1550 nm in silicon photonics.

1. Introduction
The ever-increasing data demand of modern societies requires a more efficient conversion of data signals in the optical domain, from fiber optic internet to electronic devices, like a smartphone or laptop. This conversion process from optical to electrical signals is performed by a photodetector, a critical building block in optical networks. 2D materials have scientific and technologically relevant properties for photodetectors. Because of their strong optical absorption, designing a 2D material-based photodetector would enable an improved photo-conversion, and hence more efficient data transmission and telecommunications [1,2]. However, 2D semiconducting materials, such as those from the family of transition metal dichalcogenides, have, so far, been unable to operate efficiently at telecommunication wavelengths because of their large optical bandgap and low absorption [3].

2. Results
Strainoptronics provides a solution to this shortcoming and adds an engineering tool for researchers to modify the electrical and optical properties of 2D materials, and thus the pioneered 2D material-based photodetectors (Fig. 1). Realizing the potential of strainoptronics, we stretched an ultrathin layer of molybdenum telluride, a 2D material semiconductor, on top of a silicon photonic waveguide to assemble a novel photodetector, and used their newly created strainoptronics “control knob” to alter its physical properties to shrink the electronic bandgap, allowing the device to operate at near infrared wavelengths, namely at the telecommunication (C-band) relevant wavelength around 1550 nm [4].

One interesting aspect of this work is, that the amount of strain these semiconductor 2D materials can bear is significantly higher when compared to bulk materials for a given amount of strain. We note that these novel 2D material-based photodetectors are 1,000 times more sensitive compared to other photodetectors using graphene. Photodetectors capable of such extreme sensitivity are useful not only for data communication applications but also for medical sensing and possibly even quantum information systems. In integrated photonics, specific wavelengths such as 1,550 nm are preferred due to low-loss transmission and the availability of optical gain in this spectral region. For chip-based photodetectors, two-dimensional materials bear scientifically and technologically relevant properties such as electrostatic tunability and strong light–matter interactions. However, no efficient photodetector in the telecommunication C-band has been realized with two-dimensional transition metal dichalcogenide materials due to their large optical bandgaps. Here we demonstrate a MoTe₂-based photodetector featuring a strong photosresponse (responsivity 0.5 A/W⁻¹) operating at 1,550 nm in silicon photonics enabled by strain engineering the two-dimensional material (Fig. 2) [4]. Non-planarized waveguide structures show a bandgap modulation of 0.2 eV, resulting in a large photosresponse in an otherwise photoinactive medium when unstrained. Unlike graphene-based photodetectors that rely on a gapless band structure, this photodetector shows an approximately 100-fold reduction in dark current,
enabling an efficient noise-equivalent power of 90 pW/Hz\textsuperscript{0.5}. Such a strain-engineered integrated photodetector provides new opportunities for integrated optoelectronic systems.

Building on this 2D material detector demonstration and on the concept of strainoptronics, we recently investigated a roadmap towards achieving a high gain-bandwidth-product photodetectors exploiting the high absorption of 2D materials, photonic waveguides, and plasmonics slot waveguides [5].

Photodetectors are key optoelectronic building blocks performing the essential optical-to-electrical signal conversion, and unlike solar cells, operate at a specific wavelength and at high signal or sensory speeds. Towards achieving high detector performance, device physics, however, places a fundamental limit of the achievable detector sensitivity, such as responsivity and gain, when simultaneously aimed to increasing the detector’s temporal response, speed, known as the gain-bandwidth product (GBP). While detector’s GBP has been increasing in recent years, the average GBP is still relatively modest (~10\textsuperscript{6}-10\textsuperscript{9} Hz/A/W). Here we discuss photocarrier-based detector performance limits and opportunities based on arguments from scaling length theory relating photocarrier channel length, mobility, electrical resistance with optical waveguide mode constrains. We show that short-channel detectors are synergistic with slot-waveguide approaches, and when combined, offer a high-degree of detector design synergy especially for the class of nanometer-thin materials. Indeed, we find that two-dimensional material-based detectors are neither limited by their low mobility nor by associated carrier velocity saturation limitations and can, in principle, allow for 100 GHz fast response rates, which is unlike traditional detector designs that are based on wide channel lengths.

**Conclusions**

Here we introduce the strainoptronics – a new degree of freedom to engineer optoelectronic devices. We demonstrate a strain-induced absorption-enhanced 2D nanocrystal (MoTe\textsubscript{2})-based silicon photonic microring-integrated photodetector featuring high responsivity of ~0.5 A W\textsuperscript{-1} at 1550 nm, with a low NEP of 90 pW/Hz\textsuperscript{0.5}. Subject to mechanical strain, the bandgap shifts towards 0.80 eV for strained MoTe\textsubscript{2} when the 2D nanocrystal is wrapped around a non-planarized silicon waveguide. The local enhancement of the work function mapped out by KPFM corresponds to a local change of strain of ~3 ± 1% according to DFT calculations. We observe a 3 dB bandwidth of 35 MHz, where the response time is transit time limited. This strain-engineered bandgap enables optical absorption at 1,550 nm, resulting in an integrated photonic detector that could potentially open up a new pathway for photonic circuits.

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**References**


Semiconductor Nanocrystal Optoelectronics: Pushing the Limits

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Abstract

Semiconductor nanocrystals have attracted great interest for color conversion and enrichment in quality lighting and displays. Optical properties of these solution processed nanostructures are conveniently controlled by tailoring their size, shape and composition in an effort to realize high performance light generation and lasing. These colloids span different types and heterostructures of semiconductors in the forms of quantum dots and rods to the latest sub family of nanocrystals, the colloidal quantum wells (CQWs). In this talk, we will introduce the emerging field of semiconductor nanocrystal optoelectronics, with most recent examples of their photonic structures and optoelectronic devices employing such atomically flat, tightly confined, quasi 2 dimensional CQWs, also popularly nick named ‘nanoplatelets’. Among various extraordinary features of theirs, we will show that these CQWs enable record high optical gain coefficients [1] and can achieve gain thresholds at the level of sub single exciton population per CQW on the average [2], empowered by carefully engineering their heterostructure [3]. Next, we will present a new, powerful, large-area self assembly tool for orientation controlling of these nanoplatelets [4], which provides us with the ability to tune and master their excitonic properties in their ensemble as well as the level of achievable energy transfer among them and with other nearby species. Using three dimensional constructs of face down self assembled slabs of CQWs with monolayer precision, we will demonstrate ultrathin optical gain media and lasers of these oriented CQW assemblies [5]. Finally, we will show record high efficiency colloidal LEDs using CQWs employed as the electrically driven active emitter layer [6] and record low-threshold solution lasers using the same CQWs employed as the optically pumped fluidic gain medium [7]. Given their current accelerating progress, these solution processed quantum well materials hold great promise to challenge their epitaxial thin film counterparts in semiconductor optoelectronics in the near future.

Chiral Near-Field Properties of Plasmonic Nanomaterials: Imaging and Functions

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Abstract

Based on near-field and far-field optical activity microscopic methods, we showed gold nanostructures give highly enhanced optical activity in the local sites near the nanostructures (~10^5 times enhancement as compared with macroscopic optical activity), even in achiral nanostructures, suggesting strong chiral near-field interaction. The strong chiral near-field interaction gives highly circularly polarized luminescence from achiral dye molecules adsorbed on chiral gold nanostructures. We also demonstrate dissymmetry of optical trapping behavior of chiral gold nanoparticles.

1. Introduction

Chirality is an essential property of plasmonic materials, from the viewpoint of fundamentals of plasmon induced local fields and their interactions with molecules and nanomaterials. It is of fundamental importance to investigate internal structures (geometrical distributions) of chiral optical responses in plasmonic materials, to design chiral features of the plasmons and their functions. To analyze the chiral local optical fields, we developed far-field and near-field optical activity imaging methods that allow us to visualize local structures of optical activity in nanomaterials: (i) Near-field CD imaging, where circularly polarized light (far-field) is incident on the sample and near-field scattering intensity in the vicinity of the sample is detected through the aperture near-field probe (in some cases, near-field circularly polarized illumination and far-field optical response detection was adopted). (ii) Near-field polarimetry imaging, where linearly polarized near-field radiation is incident on the sample through the aperture probe and the polarization state (ellipticity and azimuth angle) of the scattered light (far-field) is detected as the signal for imaging. (iii) High-precision far-field CD imaging microscopic method, where circularly polarized light (far-field) is incident on the sample and the far-field transmitted intensity is detected. These methods were applied to observe local chiral plasmonic fields for 2-dimensional gold nanostructures [1]. We found very different characteristic features of local optical activity arising from the local chiral fields as compared with macroscopic optical activity. The study was extended to generation of controllable local circularly polarized fields with achiral gold nanostructures. Based on the fundamental properties of chiral optical responses obtained, we demonstrated that the chiral plasmon resonances induce highly circularly polarized luminescence from achiral fluorescent molecules. We also show dissymmetry in optical trapping of chiral metal nanoparticles.

2. Results and Discussion

2.1. Optical activity imaging of chiral plasmons

Gold nanostructures with 2-dimensional chiral geometries are known to exhibit strong optical activity in the wavelength region resonant with some surface plasmon modes. Figure 1 shows a far-field CD microscopic image of a chiral 4-fold symmetry pinwheel-shaped gold nanostructure array [2]. The CD signal is inverted when the handedness of the nanostructure is inverted. The CD signal was found to depend on the position inside the single pinwheel structure (unit cell).

![Figure 1: Far-field transmission image (A) and CD image (B) of pinwheel-shaped gold nanostructure array (at 700 nm) [2].](image)

The image contrast was more prominent in the near-field optical activity images, and the amplitudes of local CD signals were as large as 10^5 times the macroscopic CD signals of the same samples, for 2-dimensional chiral gold nanostructures. Even 2-dimensional achiral nanostructures (that do not give macroscopic CD signals) exhibited strong local optical activity arising from the local chirality [3,4]. Figure 2 shows an ellipticity image of gold nanorod obtained with near-field polarimetry imaging.

Based on the results of the achiral nanostructure, we showed that controllable local circularly polarized field can be generated by a combination of linearly polarized light and a gold nanorod [5]. When the light with polarization oblique to the nanorod axis is incident on the rod, highly circularly polarized local field can be generated, and the handedness of the circular polarization and the ellipticity can be controlled by simply adjusting the direction and the angle of the incident light.
polarization. The results may provide basic principle to get highly chiral and switchable local optical fields, which may give us a chance to pioneer analytical applications of chiral optical fields and novel optical devices.

2.2. Highly circularly polarized luminescence from fluorescent molecules induced by chiral plasmons

The strong local optical activity associated with the chiral plasmons indicates existence of highly chiral local fields, which suggests strong chiral near-field interaction between the plasmons and the materials in the vicinity of the nanostructures. We thus examined near-field interaction between dye molecules and chiral plasmons [6]. We used achiral organic dyes as fluorescent emitters with luminescence that interacts with plasmons on two-dimensional chiral gold nanostructures on a glass substrate. We found that the luminescence from the dye was highly circularly polarized (dissymmetry factor g>0.1) as compared with circularly polarized luminescence from dyes with chiral molecular structures (g<10^-3). The handedness of the polarization was determined by that of the chiral gold nanostructure. The luminescence dissymmetry spectra showed maximum amplitudes in the wavelength region that correspond approximately to the wavelength providing maximal CD of the gold nanostructure, which arise from a multipolar plasmon with a chiral structure. This result indicates that the highly circularly polarized luminescence originates in the interaction between the dye molecules and the chiral plasmon resonances.

2.3. Optical trapping of chiral metal nanoparticles

The basic principle of optical trapping of dielectric particles is the gradient force. That is, a dielectric particle is stabilized when the induced polarization interacts with the incident optical field, and therefore the particle is most stabilized at the highest intensity position of the incident light. Because a polarizability of a chiral particle depends on the handedness of the incident circular polarization, the optical force exerted on the chiral particle by right-handed circularly polarized light should be different from that by left-handed circularly polarized light. We examined the optical trapping behavior of chiral gold nanoparticles with circularly polarized light, and found that the optical force was dependent on the handedness of the incident polarization. The difference (dissymmetry of the force) was large in the wavelength region resonant with the chiral plasmon of the particle.

Acknowledgements

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References

A new spin for acoustics

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Abstract

Sound waves in fluids and gases are usually considered as scalar spinless waves. However, such waves should rather be regarded as longitudinal vector waves, with the displacement of the medium particles determining the vector field or polarization of the wave. Furthermore, structured sound-wave fields generically exhibit local elliptical polarizations and, hence, possess a nonzero spin angular momentum density. This spin density can be described within relativistic field theory, which also involves a nontrivial momentum density. I will describe general theory and specific examples of spin and momentum densities in structured sound waves. I will also consider experimental measurements and manifestations of the acoustic spin and momentum, including coupling to small probe particles. Remarkably, an analogous vector approach can also be constructed for water-surface waves. I will show theoretical and experimental results proving that water waves possess nontrivial spin and momentum densities, which can be described within a universal relativistic field theory construct. These results provide a new twist for sound and water-surface waves, and offer new fields for applications of various vector-wave phenomena, so far mostly restricted to photonic and quantum-electron systems.
Tunable Light-Matter Coupling in Low-Dimensional Excitonic Semiconductors

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Abstract

The isolation of stable atomically thin two-dimensional (2D) materials on arbitrary substrates has led to a revolution in solid state physics and semiconductor device research over the past decade. A variety of other 2D materials (including semiconductors) with varying properties have been isolated raising the prospects for devices assembled by van der Waals forces. Particularly, these van der Waals bonded semiconductors exhibit strong excitonic resonances and large optical dielectric constants as compared to bulk 3D semiconductors.

First, I will focus on the subject of strong light-matter coupling in excitonic 2D semiconductors, namely chalcogenides of Mo and W. Visible spectrum band-gaps with strong excitonic absorption makes transition metal dichalcogenides (TMDCs) of molybdenum and tungsten as attractive candidates for investigating light matter interaction and applications as absorbing media in opto-electronics. We will present our recent work on the fundamental physics of light trapping in multi-layer TMDCs when coupled to plasmonic substrates. We systematically demonstrate via calculations and matching experiments that the presence of strong excitonic resonances in multilayers (< 20 nm thickness) combined with surface plasmon excitations of the nearby metals can achieve strongly coupled modes with apparent voided crossings in reflectance spectra.

Next, we will show the extension of these results to multilayers and superlattices of excitonic chalcogenides with alternating layers of boron nitride and aluminum oxide. These hybrid multilayers offer a unique opportunity to confine light in < 3 nm thick direct band gap absorbers over cm² scale areas. We will discuss the physics of strong light-matter coupling and applications of these multilayers. Finally, we will also present our recent and ongoing works on tunable light-matter interactions in hybrid organic-inorganic perovskites where we observe exciton-polariton hybrid state emission at room temperatures in an external cavity-less geometry. Finally, I will also present our recent work on giant gate-tunability of optical constants in the telecom band in thin-films of high purity, semiconducting, carbon nanotubes. Our results highlight the vast opportunities available to tailor light-matter interactions in quantum confined materials in simple and practical designs enabling study of novel photonic phenomena and presenting avenues for practical technologies.

References:

Nanophotonics with Two-Dimensional Materials

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Abstract

Two-dimensional materials have been recently shown to host robust polaritonic modes, ranging from plasmons in highly doped graphene to excitons in transition metal dichalcogenides. The electromagnetic behavior of these modes can be well understood in terms of an effective surface conductivity, in which we can capture their strong dependence on temperature and external static electric and magnetic fields. Recent advances have also been produced in the synthesis of thin noble-metal films, which open new possibilities for exploring entirely new regimes of nanometallic plasmonics. In this presentation, we will overview the general characteristics of the optical response of these materials, which can be understood in terms of simple theoretical models. We will also cover more sophisticated descriptions, aiming at exploring genuinely quantum-mechanical effects. We will further overview recent advances in the fields of ultrafast optical response and nonlinear optics, as well as the potential application of these materials in light modulation, quantum-optics, and optical sensing. We will discuss the in/out-coupling problem between external light and polaritons of short wavelength. Theory and experiments will be discussed for graphene, atomically-thin silver films, and monolayer hexagonal boron nitride as genuine examples of ultraconfined polaritons of plasmonic of phononic nature, offering the possibility to reach the quantum coupling regime with single emitters and displaying strong nonlinear effects.
Wavelength conversion through plasmonic photoconductive nanostructures

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Abstract
Detection of faint fluxes of photons at terahertz frequencies is crucial for various applications including biosensing, medical diagnosis, chemical detection, atmospheric studies, space explorations, high-data-rate communication, and security screening. Heterodyne terahertz spectrometers based on cryogenically cooled superconducting mixers have so far been the only instruments that can provide high spectral resolution and near-quantum-limited sensitivity levels. The operation temperature, bandwidth constraints, and complexity of these terahertz spectrometers have restricted their use to mostly astronomy and atmospheric studies, limiting the overall impact and wide-spread use of terahertz technologies. Here we introduce a spectrometry scheme that uses plasmonic photomixing for terahertz-to-radio frequency downconversion to offer quantum-level sensitivities at room temperature for the first time. Frequency downconversion is achieved by mixing terahertz radiation and a heterodyning optical beam with a terahertz beat frequency in a plasmonics-enhanced semiconductor active region. We demonstrate spectrometer sensitivities down to 3 times the quantum-limit at room temperature. Our presented spectrometry scheme can be applicable to resolve both the high-resolution spectra of gas molecules and mid-resolution spectra of condensed phase samples over a total operable bandwidth of 0.1-5 THz. As an example, we use the presented spectrometer to resolve the spectral information of ammonia, which has a number of narrowband absorption peaks over the 0.1-5 THz frequency range. With a versatile design capable of broadband spectrometry, this plasmonic photomixer has broad applicability to quantum optics, chemical sensing, biological studies, medical diagnosis, high data-rate communication, as well as astronomy and atmospheric studies.
Metamaterials that travel faster than light: putting the squeeze on photons

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Abstract

"Nothing can travel faster than light" is not a correct statement. Many things can and do. Think of a wave breaking at an angle on the sea shore. The point of impact travels along the beach very fast if the angle is a shallow one and can travel infinitely quickly as the angle tends to zero. I shall speak about metamaterials in which the structure moves with a velocity close to or faster than light giving rise to phenomena not seen in static structures. The structures naturally break time reversal invariance giving rise to effects for photons that resemble electrons in a magnetic field. In another realisation the metamaterial grabs hold of the field lines of incident radiation and squeezes them into a tightly formed pulse forming a supercontinuum of intense radiation.
Commercializing Metaphotonics

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Abstract

According to a market research organization, the metaphotonics market is expected to exceed $10B in 10 years, and its growth be fueled by the rapidly spreading IoT and related services powered by the 5G network. But, what are the successful commercialization examples of metamaterials that we know?

More than a decade ago, my predecessors at Samsung recognized metasurface optics as a next-generation technology that is potentially superior to the conventional counterpart and commercially impactful. They launched small research efforts to discover the underlying fundamental principles as well as to create commercially viable metaphotonic devices. We also carried out intensive collaborative research effort with major research groups in California as well as universities around the world through our Grand Research Opportunity program. Since then, our research has substantially grown and expanded into diverse areas of metamaterials.

We expect metaphotonics to play key roles in implementing more compact, cost-effective, multifunctional imaging and sensing functionalities in mobile devices. In this presentation, I will share some of our recent results and on-going commercialization efforts for metaphotonics utilizing Si-based IC-processing technologies. A few areas of metamaterial applications include safer autonomous driving; custom-tailored point-of-care health monitoring and diagnosis; and improving light-capturing efficiency of sub-micron-pixel CMOS imagers. I look forward to share and discuss our findings and vision for the coming years.
Tunable and Time-Modulated Flat Optics

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Abstract

Metasurfaces offer tremendous opportunity for photonics, namely, to manipulate amplitude, phase, and polarization of electromagnetic waves with arrays of subwavelength nanoantennas, enabling systems with flat optical components featuring dramatically reduced size, weight and power. Currently most metasurfaces are ‘static’ and have functions that are fixed at the time of fabrication. By making the system tunable or reconfigurable in its phase, amplitude and polarization response through incorporation of electro-optical effects, one can achieve real-time control of optical functions and indeed achieve multi-functional characteristics after fabrication. Despite the real-time tunability offered by the electro-optical metasurfaces, their operation thus far has been limited to the quasi-static regime, where temporal variations are slow enough that they do not result in changes in scattered beam frequency. By contrast, time modulated metasurfaces are temporally at rates high enough to generate new frequencies. Introducing time modulation to these metasurfaces opens a four-dimensional design space which can be used to overcome several fundamental limitations associated with static and quasi-static metasurfaces. In particular, time-modulated metasurfaces can break time-reversal symmetry and lift the Lorentz reciprocity constraint, enabling realization of nonreciprocal components without magnets or nonlinear elements. Moreover, time modulation leads to generation of sidebands which provide control over the spectral content of scattered light in addition to its spatial features and can extend the degree of light manipulation through modulation-induced phase shifts and space-time photonic transitions, concepts that lie beyond the capabilities of their static or quasi-static counterparts.
Volumetric microscale gradient refractive index lenses and waveguides for ultra-dense 3D optics

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Abstract

Here, we present Subsurface Controllable Refractive Index via Beam Exposure (SCRIBE), a lithographic approach that enables the fabrication of volumetric microscale gradient refractive index lenses and waveguides. The basis of SCRIBE is multiphoton polymerization inside monomer-filled nanoporous silicon and silica scaffolds. Adjusting the laser exposure during printing enables 3D submicron control of the polymer infilling and thus the refractive index over a range of greater than 0.3 and chromatic dispersion tuning. Combining SCRIBE’s unprecedented index range and 3D writing accuracy has realized the world’s smallest (15 µm diameter) spherical Luneburg lens operating at visible wavelengths. SCRIBE’s ability to tune the chromatic dispersion alongside the refractive index was leveraged to render achromatic doublets in a single printing step, eliminating the need for multiple photoresins and writing sequences. SCRIBE also has the potential to form multicomponent optics by cascading optical elements within a scaffold. As a demonstration, stacked focusing structures that generate photonic nanojets were fabricated inside porous silicon. Finally, an all-pass ring resonator was coupled to a subsurface 3D waveguide. The measured quality factor of 4600 at 1550 nm suggests the possibility of compact photonic systems with optical interconnects that traverse multiple planes. SCRIBE is uniquely suited for constructing such photonic integrated circuits due to its ability to integrate multiple optical components, including lenses and waveguides, without additional printed supports and compatible with almost any nanostructured host as long as the host does not strongly absorb the writing laser (~800 nm) and the structure can be filled with monomer.
Design and Knowledge Discovery in Metastructures Using Manifold Learning

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ABSTRACT

New techniques for design and optimization of electromagnetic nanostructures using manifold-learning techniques are discussed. Using the strong correlation among features of an electromagnetic problem, deep-learning techniques are employed to considerably reduce the dimensionality of the problem and thus, the computation complexity, without imposing considerable error. Deep-learning algorithms can be trained to relate the reduced-dimensionality design and response spaces and facilitate the solution of the inverse design problems that are complicated to solve with conventional techniques. In addition, by training manifold-learning algorithms in the reduced-dimensionality spaces, valuable insights about the feasibility of the response and the roles of design parameters can be obtained. This talk explains the importance of these approaches and their applications to high-impact photonic nanostructures.
Active Epsilon-Near-Zero Photonics

Howard Lee, Aleksei Anopchenko, Sudip Gurung, Khant Minn, Jingyi Yang

Abstract

This talk will review our recent development on conducting oxide and metallic nitride epsilon-near-zero optics. I will present our recent advances on the study of enhanced ultrafast nonlinearity and broadband and field-effect tunable absorption in ultrathin transparent conducting oxide ENZ materials meta-film fabricated by atomic layer deposition technique. In addition, I will discuss the photoluminescence enhancement of 2D materials on epitaxial titanium nitride thin films grown by molecular-beam-epitaxy. These studies enrich the fundamental understanding of emission and nonlinear properties on ENZ thin films that could be important for the development of advanced nanoscale lasers/light sources, optical/bio-sensors, and nano-optoelectronic devices.
Publishing in Nature Journals

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Abstract
This talk, although with an emphasis on Nature Photonics, will introduce you to all the Nature journals, and cover the detailed information and guidelines on scientific manuscript preparation and submission. Also presented is an overview on the editorial and peer-review processes in all Nature journals. For those who are interested in being an editor, you will get to know the selection criteria and process of Nature journals.
Hybrid Nanomaterials and Metastructures for Photonics, Sensing and Energy
Polarization state generator obtained by self-assembled plasmonic nanoparticles

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Abstract

In this work, we explore the optical properties of gold nanoparticles assembled into chiral structure. This structure exhibits a complex multianisotropy which comes from the dipolar interaction between NPs. We show that these nanostructures are good candidates for new polarization devices.

1. Introduction

Metallic nanoparticles (NPs) hold a great potential as structural and functional building blocks for three dimensional (3D) nanostructures with specific optical applications. When GNPs are closely assembled, their localized surface plasmon resonances (LSPR) are coupled, resulting in the enhancement of the electric field in the gap between the adjacent nanoparticles. This NPs interaction gives the opportunity to build new metamaterial which control the polarization state of light.

In this context, we have investigated the optical properties of nanostructures which consist of GNPs grafted on silica nanohelices with tunable handedness [1]. This gold nanohelices are self-aligned by spray coating at grazing angle to form thin film. Mueller matrix measured in transmission, shows that these films exhibit linear dichroism and birefringence, as well as circular dichroism. We demonstrate that these multianisotropic nanostructures are good candidates for new polarization management devices.

2. Result and discussion

As shown in figure 1, two films, called F1 and F2 are investigated. F1 is composed of randomly aligned silica helices functionalized with gold NPs. On the contrary, F2 is obtained by grazing incidence spraying technique. The silica helices are aligned along the sprayed direction.

Mueller matrix measurements reveals that F1 and F2 exhibit a bisignate circular dichroism (CD) at plasmon resonance (Figure 2). The sign of the CD depends on the handedness of helices. In addition, strong linear dichroism (LD) and birefringence (LB) are observed in F2. LD reaches a maximum value at the plasmon resonance of gold NPs.

Contrary to circular dichroism, the linear birefringence and dichroism are closely related to the orientation of nanohelices. As example, the pseudo optical axes of films are found at ±45° to the nanohelices axis.
Simulations based on coupled dipole model (CDM) allow reproducing the linear and circular dichroism of films. This model takes into account the interaction between GNPs, the density and the orientation of nanohelices. These results demonstrate that the dichroism and the birefringence of films come from the plasmonic coupling of NPs organized along an anisotropic and chiral structure.

### 3. Conclusions

Gold NPs assembled into chiral structures offer a complex anisotropy. This anisotropy comes from the dipole coupling between NPs. We explore the ability to use this multianisotropic system. F1 and F2 are dominated by CD and LD, respectively. In other word, F1 can be used as circular polarizer while F2 can be exploited as linear polarizer.

**Acknowledgements**

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**References**


High quality factor Tamm structures for the development of laser sources at room temperature

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Abstract

Tamm structures offer very versatile approaches to develop confined lasers, polarized lasers or plasmon sources. We propose here an optimized design of these structures, enabling an increase by a factor 5 of their quality factor, which is a critical parameter for various applications. In particular, we will show that these optimized structures enable room temperature lasing operation. This first demonstration is an important step toward future applicative developments of Tamm devices.

1. Introduction

Spatial confinement of optical mode is a key point for emission control in nanostructures as it directly affects the emission rate. Sub-wavelength confinement is achieved with plasmonic structures, but quality factors remain lower than a few hundred. High quality factor dielectric structures based on e.g. photonic bandgaps, micropillars, mesa, can be obtained, but often at the cost of complex technological processes. Tamm modes [1] lie in between these two approaches. These modes appear at the interface between a dielectric Distributed Bragg Reflector (DBR) and a metallic layer. One of their striking features is that a very easy mode confinement can be achieved by a simple patterning of the metallic layer. This is not only a simplified technological process, but really adds new degrees of freedom and versatility in the structures which can be fabricated. Tamm structures have been proposed for various applications such as control of spontaneous emission [2, 3], polaritonic emission [4,5,6], lasing [7, 8] with controlled polarization [9], or plasmon generation [10]. Despite its interest, Tamm structures quality factor is limited to ~1000, which restricts their potential applications. In particular, all the above results were obtained at low temperature. Here, we propose a new Tamm structures design which enables an increased quality factor up to 5000. After describing the properties of these ameliorated structures, we will show that room temperature lasing operation can be achieved, which is a necessary step toward future applications.

2. Results

Transfer matrix simulations were first performed to calculate the reflectivity and the electric field associated to Tamm structures comprising a dielectric spacer of variable thickness between the DBR and the metal. We will show that when increasing the spacer thickness, the repartition of the electric field in the structure is modified, which is associated to an increase of the quality factor. In particular, for a 20 nm spacer, a quality factor of 5000 can be theoretically obtained. A sample formed by a 65 pairs GaAs/AlAs comprising InAs/InGaAs quantum dots was grown by molecular epitaxy, and covered by a 45 nm silver layer. Part of the sample comprises a 35 nm spacer inserted between the DBR and the metal layer. Angle resolved photoluminescence experiments compare the mode behavior in the region without spacer (conventional Tamm mode, Q=860, Figure 1a) and with the spacer (super Tamm mode, Q=4800, Figure 1b). The increase in the quality factors is around 5.5 for the super Tamm mode compared to the conventional Tamm mode. These experimental results are in very good agreement with the simulations, as shown in Figure 1c,d. It should be noticed that this approach also preserves the confinement possibilities offered by the Tamm structures.

Figure 1: Angle resolved photoluminescence experiments of (a) the conventional Tamm structures and (b) the super Tamm structure. (c) and (d) show the transfer matrix calculations for conventional and super Tamm structure.
However, in the structure described above, the repartition of the electrical field differs from the one associated to a conventional Tamm structure. In order to obtain a maximum of the electric field located at the metal/DBR interface, with an exponential decay in the DBR, one need to finish the DBR with a quarter wavelength layer. To do so, we designed a new 50 pairs AlGaAs/AlAs DBR in which the last layer is formed by a $\lambda/8\text{AlAs}$ layer on which a $\lambda/8\text{SiO}_2$ layer of SiO$_2$ was deposited. These two layers thus form a quarter wavelength layer with reduced effective refractive index, ensuring a lower fraction of the electric field lying in the metal and an increased quality factor. This new structure also comprises 8 GaAs quantum wells embedded in the AlGaAs upper quarter wavelength layers during the growth. Optical characterization of this structure were performed at room temperature.

Figure 2: (a) Angle resolved reflectometry of a super Tamm structure containing GaAs QWs at room temperature. (b) Angle resolved emission at room temperature under optical pumping (above threshold).

Figure 2a presents the dispersion relation obtained in reflectometry when 43 nm of silver is deposited on the DBR. A clear anticrossing between the parabolic Tamm mode and the excitonic line is visible, indicating the good quality factor of this structure. In order to reach lasing operation, a thicker silver layer of 90 nm was deposited on the sample. In this case, the laser pump cannot be transmitted through the thick silver layer. The optical pumping of the sample was thus performed on the edge of a micro-stripe engraved on the silver film. Laser operation at room temperature was obtained, as shown in the dispersion relation of the emission of Figure 2b.

3. Conclusions

In conclusion, by a proper design of the Tamm structure its quality factor can be increased, which is a critical point for room temperature operation demonstrated here but also for other developments such as polariton lasing. Furthermore, Tamm structures are also promising for electrical injection, due to the metallic layer which can ensure both optical confinement and carrier transport. The design of such electrically pumped devices will be discussed as a perspective of this work.

References

Plasmon-Induced Resonance Energy Transfer for Photocatalysis, Biosensing and Photodynamic Therapy

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Abstract
This talk presents a new energy transfer mechanism from metal to semiconductor, that is, plasmon-induced resonance energy transfer (PIRET). This talk will demonstrate the use of PIRET mechanism to design new materials and devices for solar energy conversion, photocatalysis, biosensing and photodynamic therapy.

1. Introduction
Surface plasmon resonance (SPR) can be tuned to absorb light in a wide spectral range. Also, plasmonic metal nanostructures can have large absorption cross-section. Therefore, metal nanostructures can be coupled to semiconductor to form plasmonic metal-semiconductor heterojunctions to enhance the light absorption capability of semiconductor. Plasmonic metal-semiconductor heterojunctions are considered to be a new type of materials that exhibit unique physicochemical properties, which results in a wide range of applications in energy conversion, photochemistry, photodetection, sensing and precision medicine.

2. Results
This talk shows that the PIRET process is totally different from the other two plasmonic energy transfer processes: hot electron injection and light scattering [1,2]. The PIRET process can induce electron-hole pairs through the dipole-dipole interaction between the plasmonic metal and the semiconductor.

A series of metal-semiconductor heterojunctions have been designed based on the PIRET mechanism [3,4]. For example, the Au-Cu_{2}O composite shows visible-light photocatalytic activity [4]. In addition, the PIRET mechanism has been used to design a photoelectric sensor for detection of heavy metals in water. Moreover, a complex nanostructure has been developed for photodynamic therapy [5]. The PIRET process can be used for cancer treatment.

3. Conclusions
This talk not only shows a new plasmonic energy transfer mechanism (PIRET) but also demonstrates the applications of the PIRET.

References
Hot-carrier generation from surface plasmon decay has attracted much recent attention due to its promising applications in physical, chemical, materials, and energy science. However, the detailed mechanisms of plasmonic hot-carrier generation and relaxation are less studied or treated by the semiclassical model. In this work, we developed a quantum-mechanical model and coupled master equation method to study the generation, relaxation, and extraction of hot-carriers. The plasmon excitation and hot-carrier generation from the plasmon decay are derived from the linear-response time-dependent density functional theory. And its connection to the semiclassical model is discussed. Relaxation due to electron-electron and electron-phonon scatterings are treated on equal footing. With this development, the initial distribution of hot-carriers and lifetimes of hot-carriers induced by different excitation are investigated. Moreover, the heating effect due to the hot-carriers decay is also studied. We also generalize the model to study the extraction of hot-carriers to attached molecules or semiconductors. The quantum yield of extracting hot-carriers from the plasmonic nanoparticles is found to be size-dependent and consistent with experimental measurements.
Overcoming Limits in Nano-Optical Simulations, Design and Experiments Using Deep Learning

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Abstract

Subwavelength small particles can be tailored to fulfill manifold functionalities when interacting with light. During the past twenty years, tremendous research efforts have therefore been put into the field of nano-optics, leading to astonishing results and applications like flat optics, optical cloak or negative index meta-materials. However, there are physical and/or methodological constraints which have proven hard to overcome. For instance, the optical diffraction limit is a difficult obstacle in many applications ranging from microscopy to optical information storage. In nanooptics, inverse problems like the rational design of nano-structures are another example for a difficult tasks. We show how problems that were until recently considered very hard to solve, can be tackled efficiently using methods of artificial intelligence (AI) and specifically deep learning.

1. Introduction

Deep artificial neural networks (ANNs) have shown tremendous potential in solving problems that formerly were very hard or even impossible for “classical” algorithms. As a consequence, researchers from manifold areas including medicine, biology or physics started to increasingly use methods of AI [1, 2, 3]. ANNs can be very efficient in the analysis of large (scientific) datasets for instance from microscopy, tomography or spectroscopy [1, 4]. Trained on large datasets, neural networks can also learn to efficiently predict approximate solutions to notoriously hard inverse problems [5, 6] or to solve physical models e.g. in fluid mechanics or optics [7, 8, 9]. Furthermore, in several proof-of-principle studies ANNs have recently been used for the conception of on-demand photonic nanostructures and meta-materials [5, 8, 10, 11].

Here we give an example on how ANNs can be used to drastically accelerate simulations in nano-optics and give an outlook on how this can be used for generalized inverse design of photonic nanostructures. We also show how ANNs can help in the evaluation of experimental data in nano-optics and demonstrate at a specific example how the optical diffraction limit can be circumvented using an ANN, pushing the data density in optical information storage.

2. Generalized nano-optics predictor network

In most applications of deep learning in physics, ANNs are trained on very specific problems. If the problem changes, the time-consuming training procedure including costly data generation and testing needs to be re-done from scratch. We demonstrate here how to overcome this limitation by training an ANN on a very generalized description of light-matter interaction. To this end, we describe arbitrary nanostructures in a coupled dipole approximation (CDA) [12]. A 3D convolutional deep neural network is then trained on the prediction of the CDA-calculated internal fields in an arbitrary, volume discretized nanostructure. As illustrated in figure 1 the input to the network is a volume model of the structure, and the output are the complex, time-harmonic fields at every mesh-cell. The predicted internal fields can then be used to derive manifold physical quantities in the near- and far-field region.

We show that a symmetric ANN model can be trained very efficiently on this problem and becomes capable to predict the optical response of individual nanostructures with an accuracy of around five percent [9]. We show how the approach can be extended to spectrally resolved predictions and multi-material scenarios and demonstrate how generalized inverse design can be achieved by an evolutionary optimization scheme [13], replacing the slow simulations routine by the very fast ANN model.
encode multiple bits in geometry

visible light

diffraction limit

silicon nanostructure

Deep Learning Neural Network

ANN read-out via scattering

each geometry: unique optical spectrum

light polarization: x y

wavelength

011101000

10000101

001011101

Figure 2: Up to 9 bits, encoded in a nanostructure of sub optical diffraction limit size, are decoded via their optical scattering spectrum, using an ANN for error free read-out, despite unavoidable fabrication imperfections and instrumental noise.

3. Deep learning for optical storage densities beyond the diffraction limit

Recently we developed a concept encoding multiple bits of information in the geometries of complex silicon nanostructures, each covering no more than a diffraction limited area (see left of Fig. 2). Via the optical scattering spectra we then read-out the sequences of binary data from a far-field measurement. This delicate task of data recovery through an optical measurement is however prone to instrumental noise and fabrication defects. We demonstrate how robust data read-out is possible based on an ANN, trained on the recognition of the optical scattering spectra of the topology-encoded nanostructures (right of Fig. 2). We experimentally achieve quasi-error-free readout of up to nine bits per diffraction limited area, effectively going beyond the Blu-ray data density. We show that an ANN can recover the information even using very limited spectral information like RGB color information, obtained from standard dark-field microscopy images [4]. The latter approach allows a massively parallel read-out of information encoded in many thousands of nanostructures simultaneously and together with the high bit-density is very promising for next-generation optical data storage solutions.

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References


Up- and Down-Conversions Coupled to Surface Lattice Resonances in Aluminum Periodic Arrays

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Abstract
Aluminum is known to plasmonic up to ultraviolet frequencies, while its plasmonic performance in near infrared is less explored. In this study, for the purpose of verifying that aluminum is working effectively from ultraviolet to near infrared regions, we fabricate arrays of aluminum nanocylinders with the lattice periodicity ranging from 150 to 980 nm. Amplified up- and down-conversion are exhibited by coupling emitters on top of the lattice that resonates at their excitation wavelengths. The use of aluminum is beneficial in terms of cost and material abundance.

1. Introduction
Localized surface plasmon resonance (LSPR) is a plasma oscillation of free electrons on metal surface resonating with lightwaves. It is a unique optical property of nanosized metals that accompanies strong concentrated electric field, enabling to manipulate light at nanoscale. Aluminum (Al) is a plasmonic material working in the ultraviolet region thanks to its high carrier density. Although its plasmonic ability in ultraviolet is well-studied, the properties as well as applications of Al nanostructures in near infrared is less exploited up to now. Given the benefit of Al as the plasmonic material, i.e., low-cost, abundance in earth’s crust, and compatibility with the nanofabrication process, the use of Al in near infrared is advantageous for practical applications.

Plasmonic periodic lattice has advantages in tuning the spectral positions of resonances simply by the periodicity to induce in-plane diffraction. Especially when the LSPRs are excited at the spectral position of diffraction, both LSPRs and in-plane diffraction occur simultaneously to induce the hybridized mode called surface lattice resonance [1-3]. Al has large carrier density and responds up to ultraviolet light, and thus the periodic lattice comprising Al nanocylinder should have a large spectral tunability in inducing surface lattice resonance.

In this study, we show the spectral tunability of surface lattice resonance from ultraviolet to near-infrared using Al nanocylinder lattices with different periodicities. We use the surface lattice resonance to enhance the up-conversion (UC) and down-conversion (DC). By combining the emitter layers with a lattice resonating at the excitation wavelength, the enhancement of UC and DC are realized.

2. Experimental Section

2.1. Fabrication of Al nanocylinder array
An Al thin film was grown on a SiO\(_2\) glass substrate using electron beam deposition. The thin film was then patterned using a combination of nanoimprint lithography (EntreTM3, Obducat) and reactive ion etching (RIE) (RIE-101iPH, Samco) to fabricate the Al nanocylinder arrays. First, the resist (TU/2-170, thickness: 200 nm) was coated onto the Al thin film and prebaked for 5 min at 95 °C. As a master mold for the nanoimprint lithography, Si molds consisting of triangle arrays of nanopillars were fabricated using electron-beam lithography (F7000s-KYT01, Advantest) and Si deep etching (RIE-800iPB-KU, Samco). Next, the surface structures of the Si molds were transferred to the resist by nanoimprint lithography. The triangle arrays of Al nanocylinders were structured by RIE under a gas flow of N\(_2\) and Cl\(_2\).

2.2. Preparation of UC and DC layers on Al nanocylinder array
As a DC emitter, tris(hexamethylcyclotriisiloxane) europium bis(triphenylphosphine oxide), (Eu(hfa))\(3\)(TPPO)\(2\), where Eu\(^{3+}\) is an emitting center, was selected. [4] An Eu(hfa)\(3\)(TPPO)\(2\) layers on the substrates were prepared by vacuum evaporation. As UC emitters, the CaF\(_2\):Er\(^{3+}\),Yb\(^{3+}\) UCNPs were prepared by hydrothermal method. [5] We also prepared β-NaYF\(_4\):Yb\(^{3+}\),Er\(^{3+}\)/β-NaYF\(_4\) core-shell NPs by soft-chemistry.

3. Results and Discussion

3.1. Up-conversion coupled to surface lattice resonance
We design the size of nanocylinder and the period of the lattice so that the LSPRs and in-plane light diffraction spectrally overlap around the wavelength of 980 nm, which corresponds to \(^{2}F_{7/2} \rightarrow ^{2}F_{5/2}\) transition of Yb\(^{3+}\). A dense and transparent layer of upconverter is deposited on the array. We have observed a huge enhancement of the UC that is noticeable by the eyes (Fig. 1). By further optimizing the
configuration of both UCNPs and the lattice, we have observed an enhancement more than 100 times.

![Image](image_url)

Figure 1: Top-view SEM images of (a) the lattice and (b) the CaF$_2$-Yb$^{3+}$, Er$^{3+}$ NPs layer on the array. Photographs of the of CaF$_2$: Yb$^{3+}$, Er$^{3+}$ NPs layer on the glass substrate (No array) and on the array (With array), (c) under white light, and (d) upon irradiation with a $\lambda = 980$ nm laser in dark.

3.2. Down-conversion coupled to lattice mode

The DC luminescence from the DC layer on the Al nanocylinder array increases in intensity compared to the same layer on unstructured substrate (see Fig. 2). Extinction spectrum shows that the sample has an extinction band at $\lambda = 325$ nm, corresponding to the wavelength of excitation He-Cd laser, due to surface lattice resonance. Numerical simulation further confirms that the excitation light is trapped in the DC layer, which facilitates the strong emission.

![Image](image_url)

Figure 2: Normalized DC spectra of the Eu(hfa)$_3$(TPPO)$_2$ thin layers on the Al nanocylinder arrays with the period $= 200$ nm and on unstructured glass substrate. The inset shows the experimental configuration: The samples were excited at $\theta_{in}=0^\circ$ from the substrate side at $\lambda = 325$ nm (CW He-Cd laser), and PL was detected at $\theta_{em}=10^\circ$ from the emitter film side.

4. Conclusion

In conclusion, we have demonstrated notable enhancements of up- and down conversions using a series of Al nanocylinder array supporting surface lattice resonance in a spectral range from ultraviolet to near infrared. Surface lattice resonances are tuned by the size of nanocylinder and the period of the array which determines the spectral positions of LSPR and in-plane diffraction, respectively. Spectral overlap between them results in very strong resonance. For up-conversion, we tune the surface lattice resonance at $\lambda = 980$ nm to facilitate the $\text{^2F}_{7/2} \rightarrow \text{^2F}_{5/2}$ transition of Yb$^{3+}$. Optimization results in the huge enhancement up to 100 times. For down-conversion, the surface lattice resonance is tuned at $\lambda = 325$ nm facilitating the absorption of the emitter to enhance the emission of Eu$^{3+}$ around $\lambda = 620$ nm. The results confirm that arranging Al nanocylinder in periodic lattice is beneficial to fine-tune the resonance making full use of the responsibility of Al up to ultraviolet frequency and the tunability of in-plane diffraction by the periodicity.

Acknowledgements

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References


A bottom-up approach to the fabrication of optical metamaterials utilizing the self-assembly of silver dodecahedral clusters

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Abstract

In the production of optical metamaterials a key requirement on the comprising ‘meta–atoms’ is a light–induced magnetic response of similar magnitude to the induced electric response. It is desirable to achieve the assembly of such materials through bottom–up approaches, which require the production of colloidal dispersed ‘meta–atoms’. However, many of the currently realizable candidate colloidal particles present too weaker magnetic response for them to be utilized in this role. Hence, there is a need to for novel artificial meta–atoms with increased magnetic polarizability.

Previously, we presented our synthetic approach to the creation of suitable ‘meta–atoms’ in the form of a silica core decorated by 12 gold satellite particles (gold dodecапods, Au DDPs). We demonstrated that the optical magnetism of these objects arises from tangential polarization currents. The induced magnetic moment is analogous to that produced by circulating eddy (Foucault) currents in metals. The regular organization of the satellites around the core is more efficient than a random distribution of satellites for the generation of a circular current mode. Optical characterisation of such particles has shown them to be strong candidates for use as Huygens sources, and potential building blocks for the assembly of metamaterials.

We have subsequently improved the magnetic response of these particles through replacement of the gold with silver, [1] lowering optical losses by using a metal with a significantly higher plasmonic quality factor. [2] In this talk, we will present these improvements to the synthesis of DDPs alongside our ongoing work to build assemblies of these particles into real world metamaterials through bottom–up approaches.

Introduction

Optical metamaterials are ensembles of nanoresonators that exhibit unusual optical properties, otherwise unattainable in natural materials. One such property, a negative effective refractive index, first explored theoretically by Veselago in 1968, [3] was famously experimentally realized in 1999 by Smith et al, who produced a composite medium possessing both a negative permittivity and permeability (i.e. a negative refractive index material). [4] Since this achievement, a wide variety of novel metamaterials have been developed, enabling the production of extraordinary optical devices such as invisibility cloaks and hyperlenses. [5,6] The range of applications of metamaterials has grown to include media enabling control of the propagation of acoustic, mechanical, thermal and seismic waves.

Until now, most optical metamaterials have been fabricated using top–down lithographic approaches, typically limiting the area of such metamaterials to below 100 μm². Bottom–up approaches negate this problem, allowing the synthesis of nanoresonators and the fabrication of the metamaterial to be completed as separate steps, referred to as hierarchical self–assembly. [7] This approach allows complex nanoparticles with desirable electrical and magnetic properties to be synthesized as colloidal dispersions, and then assembled into structures on scales unachievable via top–down approaches.

Previously, our group has shown that assemblies of particles consisting of a dielectric core decorated with a disordered monolayer containing a large number of plasmonic nanoparticles (plasmonic raspberries) present a non–natural magnetic permeability. [8] We also demonstrated that well–controlled geometrically ordered
arrangements of 12 gold satellites significantly increases the obtainable magnetic dipole. [9] This magnetic moment could be increased further by using a metal with lower optical losses such as Ag in the satellites.

Taking this work forward, we are now seek to create metamaterials from our DDPs, which are extremely promising candidates.

**Results**

Highly symmetrical clusters were prepared via a multistep synthesis from dodecahedral–dimpled silica particles. The details of the synthesis are soon-to-be published [1], they are similar to our previously reported protocol utilizing Au [9]. The twelve silver satellites are arranged symmetrically around a 160 nm silica core (fig. 1).

The optically induced magnetic response of the Ag DDPs was measured by polarization–resolved static light scattering spectroscopy (fig. 2) and single particle scatter spectroscopy. The ratio of the magnetic to electric scattering is increased by a factor of ~6 compared to that of Au–DDPs with the same amount of metal. These results demonstrate the significantly reduced optical losses seen in silver. Hence, Ag DDPs are good candidates as Huygens sources for use in metamaterials.

This increase in the magnetic response is of a similar magnitude to that observed when replacing Au with Ag on our previously reported plasmonic raspberries [8]. However, the more uniform separation of the plasmonic satellites of the Ag DDPs, means that they possess a much greater response (around 6× higher than the Ag raspberries).

Numerical simulations suggest monolayers of these particles will demonstrate near–perfect absorbance at ~400 nm. Current work focuses on self-assembling the Ag DDPs into colloidal monolayers through convective-assembly. The results of these experiments will be presented alongside their optical characterization.

**Conclusions**

Bottom-up approaches offer a route to realizing large-area metasurfaces. Allowing the synthesis of highly promising candidate meta-atoms in bulk. Optimization of the particle characteristics by using Ag in the plasmonic satellites has enabled a significant increase in the induced magnetic response. Numerical calculations suggest assembling these particles into a 2D-array will yield a metasurface capable of near-perfect absorbance. Self-assembly methods will be employed to create Ag DDP monolayers to experimentally realize this result. This bottom-up approach will enable cost–effective, larger scale production of 2D and 3D metamaterials. [10]

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**References**


**Figure 2**: Ratio of axial scattering to transverse scattering, as obtained from static light scattering measurement. Ag DDPs show a significantly enhanced magnetic response (∝ axial scatter) compared with Au DDPs.
New Synthesis Approach of Aluminum Nanoparticles for UV-Plasmonics

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Abstract

Aluminum nanostructures appear to be a good alternative to gold or silver because of the broad range of their plasmonic resonances (UV to NIR) and their reduced cost. In this paper, we present a new way of synthesis of Al nanoparticles based on sonochemistry and solvothermal reaction. By tuning the solvothermal reaction time, we are able to control the size of the nanoparticles between 10 to 100nm. Finally, we will present some applications of such nanoparticles.

Aluminum colloidal synthesis appears to be more complex than other metals because the reduction of aluminum salts is complicated due to its very high redox potential and then poorly documented. Here we present a simple way based on sonochemistry and solvothermal techniques to obtain spherical and size tunable aluminum colloidal nanoparticles.

2. Synthesis

2.1. Sonochemistry

In sonochemistry, the broad range of acoustic frequencies (from 10kHz to 10MHz) and the control of the temperature provide a wide variety of parameters to be studied. Nowadays, it is well-known that acoustic waves lead to a powerful physical phenomenon, known as cavitation, that creates high-energy bubbles in the solution (with a very high pressure and temperature). The bubble’s explosion breaks chemical bonds and/or destroys solid component surface. This process is commonly used in the synthesis of nanoparticles with different metallic precursors allowing for obtaining different sizes and shapes [5]. In our study, we use this powerful method to reduce aluminum foil into aluminum precursors.

2.2. Solvothermal Chemistry

As for sonochemistry, solvothermal method is used for the high energy it provides. The main difference occurs in the mechanism, in which the solvent is heated up to its boiling point under pressure. Even if this technique is widely used to synthesize metallic nanoparticles, a void still remains concerning the case of aluminum [6].

We demonstrate that with the adapted solvent and the use of the Al’s precursors made by sonochemistry, we are able to synthesize aluminum spherical nanoparticles with a diameter ranging from 15nm+/-5nm to 100nm+/-7nm.

2.3. Results

Figure 2 presents the evolution of the Al NPs size by a daily sampling during the solvothermal step. A careful analysis of the SEM images allows us to obtained the size distribution of the synthesis as a function of the time of thermal annealing.

Figure 1: Schematic representation of the new synthesis of colloidal aluminum nanoparticles.

1. Introduction

Aluminum nanostructures provide higher plasma frequency than gold or silver that lead to a broad range of plasmonic responses from UV to NIR [1]. Moreover, this metal enters in the rock-forming minerals meaning abundance and low cost compared to noble metals [2]. Currently the main ways developed to obtain aluminum nanostructures are based on top-down techniques (lithography’s, laser ablation…) [2]. In presence of O₂, there is the formation of an Al₂O₃ layer of 3nm thick which acts as a passivation layer. However, in aqueous solvents, the lifetime of such nanostructures is strongly reduced thus limiting their potential for biological applications [3]. Nevertheless, a lot of biological experiments occur in the UV range and aluminum nanostructures could help to enhance fluorescence detection. Consequently, it is of first importance to be able to work in organic solvents [4].
Thus, the histogram distributions showed an evolution of the size from 10 to 100 nanometers with a strong increase of the polydispersity from day 14.

Figure 2: Evolution of the size of aluminum nanoparticles as a function of the time spent in the solvochemistry step (SEM images and histograms of samples from day 4 to day 14 are shown).

2.4. Characterization

The internal structure of the obtained nanoparticles has been characterized by High Resolution Transmission Electron Microscopy (HRTEM) (The Markovich research group, Tel Aviv University). The particle appears monocrystalline, the measured reticular planes correspond to the (111) and (200) family of planes in the Al cubic F system, confirming the metallic nature of the nanoparticle. Moreover an amorphous layer of aluminum oxide is measured to be 2-3nm thick.

Furthermore, optical UV-Visible spectrum in solution have been performed showing a perfect matching with calculations made using the Mie theory. However, the physical meaning of the obtained measurements is quite challenging due to the size distribution in the solution. Then, a home-made confocal microscope allows us to measure a single Al nanoparticle deposited onto a quartz substrate.

3. Conclusions and perspective

A clear synthesis method of colloidal Al nanoparticles with a controlled diameter ranging from 15nm to 100nm has been demonstrated. Upcoming experiments will focus on the modification of the shape and the synthesis of other metallic nanoparticles with this method.

Moreover, we are now using these nanoparticles through functionalization experiments in order to do metal enhanced fluorescence in UV.

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References

Gold nanostructures devices on flexible substrate for strain optical monitoring

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Abstract
Gold nanoparticles dimers (GNDs) can be used as sensitive optical sensors for the detection of local nano-deformation. There is a growing interest for sensor technologies based on polydimethylsiloxane (PDMS) as flexible substrate, since it allows reversible strain. In this context, the present work tackles the development of organized gold nanopatterns on PDMS to improve the sensitivity of strain monitoring at nanoscale (Figure 1).

Figure 1: Schematic of the basic concept

1. Introduction
Due to the high sensitivity of the localized surface plasmon resonance (LSPR) on the gap of GNDs, they appear as a solution for manufacturing nano-deformation detectors based on plasmonic coupling. The easiest way to get tunable gap is to use a flexible substrate that leads to a broad range of LSPR position change. Figure 2 shows the variation of the LSPR wavelength depending on the gap size, i.e. the deformation of the substrate.

Figure 2: Impact of the gap on the LSPR position (FDTD)

These flexible devices have therefore a tremendous interest for both fundamental physics and industrial applications. However, the fabrication method provides disorganized pattern [1] because it is usually based on nanoparticles growth.

Here, we studied the feasibility of the project by comparing expected results with FDTD simulation and experimental data.

2. Fabrication and characterization
2.1. Manufacturing process
The pattern is designed by Electron-Beam Lithography (EBL). This technique is quite precise but do not provide to work on PDMS. Consequently, a sacrificial layer is deposited on a silicon substrate before the EBL process. Subsequently, the GNDs pattern is functionalized and the PDMS mold on. The final step is the etching of the sacrificial layer and the peel-off of the device [2].

2.2. Extinction spectra under strain
The samples manufactured are then characterized with a confocal optical microscope adapted with a tensile testing machine to follow the change on the LSPR position with the increase of the strain (Figure 3). For each step of applied stress, we obtain an extinction spectra of such GNDs. As the dimer is transversally oriented to the strain, a redshift of the LSPR position is expected as calculated Figure 2.

Figure 3: Schematic of the experimental setup
3. Results and hypothesis

3.1. Asymmetric mode

Figure 4 shows a classical extinction spectrum of an ensemble of GNDs. These extinction spectra are asymmetric, while the coupling mode should correspond to a Lorentz curve. After treatment, we notice that each spectrum are a convolution of two coupling modes. One is corresponding to the dipolar mode in the air, the other one in the PDMS.

![Figure 4: Extinction spectra deconvoluted](image)

3.2. Blueshift

After analyze of the pic position in function of the strain, we notice that the LSPR blueshift instead of redshift as explained previously. Our hypothesis to explain this phenomenon is a shift center to center of the GNDs as visible Figure 5. This change on the alignment with the polarization will make appear the resonance of a single nanoparticle and explain the observed blueshift.

![Figure 5: Schematic of the hypothesis and FDTD simulation](image)

4. Conclusion and futur development

We are now able to fabricate and optically characterize GNDs devices. However, there are still opportunities for improvement. The first one is to get a better control of the manufactured device, especially the GNDs orientation. Another point is to characterize the real displacement of the particles under strain, for this Atomic Force Microscope (AFM) and Scanning Electron Microscope (SEM) in situ will be performed. We also plan to optimize the plasmonic coupling by changing the shape of the particle (Figure 6). Indeed, it is well known that bowties, for example, provide a better enhancement of the electric field [3].

![Figure 6: Impact of the shape on the plasmonic cooling (FDTD)](image)

Acknowledgements

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References


Non-Hermitian Approach for Modelling Hybrid Quantum Dot/Plasmon Systems

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Abstract

A non-Hermitian model for modelling quantum dot/plasmon interactions including dissipation and dephasing is analysed. Optical spectra in the linear regime are adequately described and the model also describes time-dependent coherences qualitatively when both dissipation and dephasing are present, and quantitatively with neglect of dephasing. Results for a large number of quantum dots allow assessing the role of coupling disorder. Interestingly, disorder can help stabilize the ensemble average towards a dark steady-state, a result of potential relevance to sensing applications.

1. Introduction

Time-dependent or time-independent Schrödinger equations with Hamiltonian operators that are not Hermitian are of both fundamental and practical interest [1, 2]. The non-Hermitian terms in the Hamiltonian are designed to describe processes such as interaction with an environment that are not explicitly included as degrees of freedom in the Hamiltonian. While the non-Hermitian approach is not as rigorous as other open quantum systems approaches such as the Lindblad master equation [3], it can offer dynamical insights and computational advantages. Recently, several papers have, in fact, studied aspects of quantum plasmonics with such non-Hermitian Hamiltonians [4-7].

In this contribution we discuss the recent results we have obtained on a non-Hermitian model to describe the dynamics of hybrid systems composed of one or more quantum dots (or excitons) coupled to a plasmonic cavity [7].

2. Non-Hermitian Model

The model involves solving the following time-dependent Schrödinger equation (TDSE),

\[ i\hbar \frac{d}{dt} \Psi(t) = H_c(t)\Psi(t) , \]

with the non-Hermitian Hamiltonian given by

\[ H_c(t) = \hbar \omega_0 \left( 1 - i \frac{\Gamma}{2} \right) \sum_j \sigma_j^+ \sigma_j + \hbar \omega_{pl}(1 - i \frac{\gamma_{pl}}{2}) b^* b + \hbar g \sum_j (\sigma_j b^* + \sigma_j^* b) - \mu E(t) . \]  

Equation (2) is consistent with a system of two-level quantum dots (energy spacing \( \hbar \omega_0 \), lowering operators \( \sigma_j \)) interacting with a plasmonic system (energy spacing \( \hbar \omega_{pl} \), annihilation operator \( b \)) with dot-plasmon coupling energy \( \hbar g \). We have also allowed for dipolar coupling to an applied electric field via the \(-\mu E(t)\) term. The non-Hermitian aspect arises from the imaginary terms involving \( \gamma_{pl} \) and \( \Gamma \), the plasmon decay rate and effective quantum dot decay rate, respectively. Note that \( \Gamma = 2\gamma_{pl}^2 + \gamma_1 \), with \( \gamma_1 \) being the spontaneous decay rate and \( \gamma_{pl}^2 \) being the pure dephasing rate. See Figure 1(a) for a schematic of the system.

One can solve the TDSE numerically, as described in Ref. [7] or, depending on the problem, develop analytical solutions.

Figure 1: (a) Schematic diagram of many quantum dots (red) interacting with a plasmonic system (gold), with one highlighted dot being excited initially. (b) Ensemble-averaged concurrence for fifty quantum dots with mean coupling 0.0835 eV. Top to bottom correspond to standard deviations of 0, 0.13 and 0.25 times the mean coupling value.
3. Results and Discussion

In Ref. [7] we examined the limits of applicability of the model outlined in Section 2, and presented some interesting results concerning disorder in the dot-plasmon couplings. We will briefly outline our analysis of the applicability of the model and concentrate more on the disorder study.

We first studied systems composed of one or two two-level quantum dots interacting with a plasmon, as in Refs. [8–10]. These latter references employed the more rigorous Lindblad density matrix formalism to obtain optical spectra and time-dependent populations that could exhibit coherent oscillations. The systems in Refs. [8, 9] are parameterized to correspond approximately to chemically synthesized CdSe quantum dots attached to gold nanoparticles, with dot-particle distances being on the order of a few nanometers. The systems in Ref. [10] are more complex ones with gold nanowells and particles. We found that optical spectra in the linear regime for all these cases can be adequately described by the non-Hermitian approach. However the model can fail under continuous optical driving in some circumstances. In the case of two quantum dots interacting with a plasmon, the model can also describe coherences and entanglement qualitatively when both dissipation and dephasing are present, and quantitatively in the limit with no dephasing.

It is interesting to consider a scenario wherein one has many quantum dots interacting with a plasmon, e.g. fifty quantum dots. This system would be very challenging with any approach if the full Hilbert space is represented. However, if one imagines one dot being initially excited via an optical pulse and is interested in the subsequent dynamics, then one can focus on the “single excitation manifold,” i.e., only include in the wavefunction representation states with one excitation. In this case, as shown in Ref. [7], one can analytically solve the problem, i.e. determine all the complex eigenvalues and eigenvectors of Eq. (2) (without the driving term) that would contribute to the time evolution. We were actually able to solve the problem for a generalization of Eq. (2) that allows for inhomogeneous dot-plasmon couplings, i.e., replace “… \( h \sum_j \cdots \)” with “… \( h \sum_j \hat{g}_j \cdots \)” in Eq. (2).

We used the analytical solution described above to assess the role of coupling disorder for fifty quantum dots interacting with a plasmon, Figure 1(b). The dot-plasmon couplings were randomly drawn from a normal distribution with parameters given in the caption and the ensemble average of the time evolution of the concurrence, a measure of entanglement, is displayed. The quantum dot and plasmon decay constants, important for the systems achieving steady-states, were \( \hbar \Gamma = 0.0017 \) eV and \( \hbar \gamma_{pl} = 0.033 \) eV, respectively. Figure 1(b) shows that, on average, large enough disorder can help stabilize the ensemble average of the open quantum system towards a dark quasi-steady-state much faster than without disorder. Such results may be useful for sensing applications or other quantum applications that could make use of ensemble averages, e.g. arrays of sensors.

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References

Plasmonics of thermoresponsive nanocomposite metasurfaces

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Abstract

Gold/PNIPAM core-shell nanoparticles (NPs) possess proven photothermal and sensing capabilities. In this contribution we report in situ spectroscopic ellipsometry (SE) measurements to determine the complex, temperature-dependent properties of ordered lattices of such NPs. The approach proposed here is instrumental to the analysis and design of functional hybrid metasurfaces with plasmonic functionalities, including particle-to-film coupled systems.

1. Introduction

Under proper conditions, thermoresponsive polymers allow to tune the plasmonic properties of plasmonic nanoparticles. This concept opens various possibilities for thermo-optical sensing, and can be conveniently exploited by creating large-scale, ordered and self-assembled lattices of metal/polymer core-shell NPs. Among the many possible metal/polymer combinations, Au/PNIPAM is one of the most appealing.

PNIPAM is a thermoresponsive polymer which undergoes a volume phase transition (VPT) if heated in aqueous environment above its lower critical solution temperature of 32 °C. Across the VPT, the PNIPAM isopropyl groups change conformation, causing the interactions among the polymer chains to transition from hydrophilic to hydrophobic. As a result, a significant reduction of volume and an increase of refractive index occur in PNIPAM. Therefore, by combining Au and PNIPAM into coreshell nanoparticles (NP), it is possible to tune the LSPR of the Au cores by varying the temperature of the PNIPAM shells.

In this contribution, we will report a study of the optical properties of coreshell Au/PNIPAM NPs, self-assembled in a hexagonal lattice and supported by a silicon substrate. We performed in situ SE measurements at different temperatures to study how the VPT of the PNIPAM shells modifies the optical properties of the coreshell NPs (Fig. 1). Through a dedicated parametric modeling of the SE data, we were able to calculate the effective complex permittivity of the NP lattice, thus determining not only the temperature-induced spectral shift in the LSPR but also the complex optical response of the lattice in a broad spectral range. Moreover, the model allowed us to estimate temperature-dependent parameters such as the distance between the NP cores and the substrate which may play a significant role in determining the optical properties of the lattice but are not easily obtained through direct measurements. The insights provided by the characterization of such hydrogel plasmonic system are also instrumental in designing, screening, and validating the functionalities of a wide range of temperature-dependent hybrid metasurfaces.

Figure 1: In situ SE spectra (top: $\Psi$; bottom: $\Delta$) measured on the Au/PNIPAM NP lattice.
2. Results

2.1. Experimental

A self-assembled lattice of Au/PNIPAM NPs [2] was fabricated on a Si substrate; its optical properties was assessed through in situ SE for temperatures between 23 and 44 °C [1]. Across this temperature range, the PNIPAM undergoes its VPT and, as a result, the LSPR of the NP lattice redshifts and become more intense. This dynamics highly depends on the lattice and NP parameters, such as interparticle distance, NP size, and the optical properties of the constituent materials.

2.2. Modelling

The interpretation of SE data requires an optical model which takes into account both the morphological and optical properties of the system. We built our model as a 3-layer stack, where - from bottom to top - we included the Si substrate, the NP lattice and the ambient (water). The lattice was modelled through a dedicated Effective Medium Approximation (EMA) based on the theoretical description by R. G. Barrera et al. [3]. In this kind of EMA, each NP in the lattice is represented as a point dipole, and the retardation effects of the EM fields inside the NP are calculated by using the modified long-wavelength approximation. To calculate the complex permittivity of the EMA layer, the algorithm takes into account the core-shell structure of NPs and their image dipoles induced in the substrate. The details of the model are reported in Ref. [4].

3. Discussion

The presence of the substrate, which is necessary to create a large-area thermoresponsive metasurface, makes it necessary to study in situ the temperature-dependent optical properties of Au/PNIPAM NP lattice. SE data and modelling allows to retrieve relevant parameters, such as the distance between the NPs core and the substrate, which are not accessible through direct measurements (Fig. 2).

4. Conclusions

The methods and analysis described here can be adapted to study the optical properties of different kinds of hybrid metasurfaces based on functional nanoparticles. For example, responsive particle-to-film-coupled systems have recently attracted much interest; in these systems, the spacing between the metallic core of NPs and the metallic substrate plays a key role in determining the optical properties. Our approach could be used to calculate that spacing along with the complex optical properties of the system. Indeed, the main application of this work lies in the possibility to quantitatively evaluate the key temperature-dependent functionalities of hybrid plasmonic metasurfaces that can be exploited, for example, as sensors or heat sources at the nanoscale.

Acknowledgement

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References

DNA Based Optical Nano-sensor for Hazardous Molecules Detection

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Abstract

The prolonged use of toxic pesticides in agriculture lead to their introduction into the food chain through food and water which results in the interaction of these toxic molecules with DNA and could create some mutations and induce translocation leading to many diseases such as cancer. The aim of this research is to develop a Nano-biosensor which can detect chemical agents that interact with DNA and induce changes in its structure. The prime of this study is to understand the structure and properties of DNA and the chemical effects of toxic agents on its various properties and behavior. The detection approach is unique because it is based on the field enhancement from coupled gold nanoparticles (AuNPs) in solution.

1. Introduction

DNA itself is a self-assembled and very stable structure [1]. After the discovery of DNA molecule, people start to explore the applications of this molecules such as binding of it with some drugs and ligands making complexes [2,3]. There are two main ways of binding of ligands/drugs to DNA molecule: electrostatic interactions or intercalation. DNA electrostatic interactions can take place either through major or minor groove, but this type of study is of less interest. DNA intercalation binding mode comes into light when the acridine, an antitumor drug was started to use clinically in early times. So, it was observed that the DNA-acridine complex was studied as it gave rise to genetic transformation and mutates the double stranded structure [4]. It became the interested matter that how this intercalation phenomenon works, when some molecules which are in aqueous conditions starts to migrate and settles in the hydrophobic pockets i.e. between two adjacent bases of DNA, this is known as intercalation. DNA intercalation results into unwinding of helix which can add 50% more to the native twist, to accommodate the intercalator elongation also takes place as it fits inside the base pairs [5]. DNA intercalating drugs are more of research interest as it can be used in pharmaceutical as anticancer drugs. Many techniques are used to identify interaction of intercalator with DNA one of the most basic is UV spectrophotometry, HPLC-MS mass spectroscopy or X-Ray diffraction is very good technique to know the intercalation, gel electrophoresis, NMR etc. DNA conjugated to Nanoparticles has recently gained popularity due to plasmonic properties of nanoparticles which help to study the changes occurring in DNA. The flexibility of AuNPs contributes to wide range of possibilities to use them for biomedical applications. The hallmark properties of spherical AuNPs which make them exceptional for their utilization are excellent biocompatibility, shape and size-related optoelectronic properties [6], low toxicity [7], and small volume to surface ratio and make them an essential tool in bio nanotechnology. The ability of fluorescence quenching and physical properties like SPR (surface plasmon resonance) are the trademarks of AuNPs.

2. Results & Discussions

2a. UV-Visible Titrations for DNA intercalation

Atrazine (2-chloro-4- (ethylamine) -6- (isopropyl amine) -s-triazine) with molecular weight 215.683g/mol is widely used pesticide to kill all types of pests in agricultural field. Many techniques as discussed above could be used to study the interaction of any type of molecules with DNA. Pesticides such as atrazine and chlorpyrifos has aromatic structure and neutral in nature, hence they tend to intercalate with DNA than interaction.

UV spectroscopy is the conventional technique to see any change of structure and morphology of DNA.

Fig 1: Melting Profile of 500nM dsDNA with increasing concentrations of Atrazine @260nm.
Figure 1 shows the variation of the melting temperature ($T_m$) of dsDNA (double strand DNA) probed at 260 nm in presence of different concentration of Atrazine. In our experimental study we observed that as the concentration increases from 4µM to 32µM the $T_m$ decreases. It shows that DNA becomes unstable when atrazine is added to it. dsDNA itself has the melting temperature of 66 °C, but when 32µM atrazine is added, $T_m$ is dropped to 62°C.

As model molecule, we use Ethidium Bromide (EtBr) which is a cationic dye usually used when fluorescence is needed to be observed. Due to its heteroaromatic type structure can settle between base pairs very efficiently and intercalation can be studied easily. Free EtBr

![Absorbance vs Wavelength](image)

**Fig 2**: Shift of spectrum to 535nm when DNA is added to EtBr molecules usually absorb at 460 nm for an emission around 610 nm. The figure 2 shows the variation of the absorption of EtBr molecules in presence of DNA. Our experimental studies show that as DNA binds to EtBr there is a decrease in the maximums of the absorption spectra as well as the decrease is accompanied by the spectral shift. EtBr shows the peak at 480nm but when mixed with DNA peak are shifted to longer wavelength of 535nm. The reason comes that there are some bound and some free EtBr molecules in the solution giving different absorption. As soon as all the binding sites of DNA are blocked there is the decrease in the $A_{max}$ at 480nm and the shift to longer wavelength is seen.

2b. DNA-AuNP Conjugation:

![SEM images of gold dimers formation in solution](image)

**Fig3**: SEM images of gold dimers formation in solution

DNA could be used to functionalize AuNP and this control aggregation of colloidal gold solution. Gold nanoparticles have inert surface, but it could be easily functionalized with biomolecules such as DNA, mRNA or proteins via sulfur end of thiol group. DNA-AuNP [1] conjugates were formed with 60nm AuNPs. Figure 3 shows SEM images of dimers formed by two AuNP and a dsDNA.

3. Conclusion:

As initial steps of the study have been a success i.e. DNA-Toxic molecules intercalation and DNA-AuNPs Dimer formation. So, our future insight is to collaborate both methods and make an optical biosensor to test the DNA intercalation with toxic molecules.

4. Acknowledgements

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5. References:

On the mechanisms of plasmon-enhanced chiroptical response

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Abstract

We present a rigorous theory based on the resonant state expansion that allows us to analyze all electromagnetic contributions to the plasmonic enhancement of the chiroptical response of chiral media. Potential applications are optimized optical sensors for molecular handedness detection.

1. Introduction

Detecting the handedness of chiral molecules is of utmost importance for chemical, biological, and pharmaceutical applications, since the handedness of a molecule determines its interaction with the environment. This includes chemical interactions as well as the interaction with light. Hence, it is possible to determine the handedness of chiral molecules by optical measurements, but the chiroptical response of such molecules is usually rather weak. Therefore, conventional approaches require using large numbers of chiral molecules.

Plasmonic nanoantennas can enhance the chiroptical response of chiral media, as indicated in Fig. 1. We have recently shown that the electromagnetic enhancement of the circular dichroism, which manifests itself as the difference in absorption of left- and right-handed circularly polarized light, can be as high as three orders of magnitude [1]. Hence, plasmon-enhanced circular dichroism spectroscopy yields a promising approach for determining the handedness of few molecules. However, little is known about the underlying enhancement mechanisms.

2. Discussion

To address this problem, we have recently extended the so-called resonant state expansion to chiral media [2]. The basic idea of the resonant state expansion is to determine a finite number of resonant states in a reference system, and to use these resonant states as a basis in order to calculate the resonant states in a perturbed system. Particularly, we expand the electric and magnetic fields of the perturbed resonant states $E_\nu$ and $H_\nu$, respectively, in terms of the unperturbed states with fields $E_n$ and $H_n$:

\begin{align}
E_\nu &= \sum_n b_n E_n, \\
H_\nu &= \sum_n b_n H_n,
\end{align}

(1)

Knowing these resonant states, we can then also construct the far-field response of that system [3, 4].

A homogeneous and isotropic chiral medium can be described by the following constitutive equations:

\begin{align}
D &= \varepsilon E - i\chi H, \\
B &= \mu H + i\chi E.
\end{align}

(2)

Here, the electric displacement $D$ is not only linked via the permittivity $\varepsilon$ to the electric field $E$, but also to the magnetic field $H$ via the Pasteur parameter $\chi$. Similarly, the electric field contributes proportional to $\chi$ to the magnetic induction $B$. Since the Pasteur parameter $\chi$ is usually a rather small quantity, we can further reduce the resonant state expansion to lowest-order perturbation theory in order to calculate the perturbed resonant states and the corresponding far-field response. Thus, we obtain analytic expressions for different contributions to the plasmonic enhancement mechanisms.

First, chirality may result in shifts of the resonance frequency that depend on the handedness of the chiral medium. Not surprisingly, this requires resonant chiral near fields with the electric and magnetic field being partially collinear, i.e., $H_n \cdot E_m \neq 0$. For achiral antennas, it turns out that this condition might be fulfilled locally, but integrating over all local contributions can cancel out the resonance shift completely.

Second, different resonant states can be coupled by the chiral medium, which impacts the circular dichroism signal whenever two or more resonant states are spectrally close and $H_m \cdot E_n \neq 0$ for $n \neq m$. Again, different local contributions might compensate each other, so that one
might consider in experimental realizations to prevent chiral molecules from entering certain areas of the local near fields in order to avoid this cancelation.

Third, the chiral medium induces chirality even in achiral resonators. This contribution requires a coplanarity of the resonant near field and the incident field in the form $\mathbf{H}_n \cdot \mathbf{E}_{\text{inc}} \neq 0$ and $\mathbf{H}_{\text{inc}} \cdot \mathbf{E}_n \neq 0$, as already argued in Ref. [1] on the basis of numerical calculations.

Our theory now provides explicit expressions for all these contributions that follow from Maxwell’s equations by first principles. These expressions can be analyzed for gaining a better understanding of plasmon-enhanced chiroptical spectroscopy in order to address the question how to optimize the plasmonic enhancement mechanisms.

Finally, it should be noted that our theory is not limited to chiroptical spectroscopy but can be applied to any sort of optical sensor that traces small changes of the electromagnetic response such as the refractive index of an analyte material [5].

3. Conclusions

Using lowest-order perturbation theory for chiral media, we obtain analytical expressions for the plasmonic enhancement mechanisms of the chiroptical response. Our approach enables an optimization of this enhancement for sensing applications.

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References


Plasmonic nanostructures for solar fuels generation

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Abstract
The development of large-scale solar energy conversion technologies for fuels and chemicals is currently hindered by low yields and scarce product selectivity. Plasmonic nanostructures have emerged as a promising building block to enhance light-matter interaction in solar fuel devices and to trigger alternative reaction pathways. In this talk, I will summarize our recent results about the integration of plasmonic nanoantennas and nanoparticles in systems for solar fuels generation, discussing the fundamental mechanisms underlying the observed enhanced reactivity.
Active optical antennas driven by hexagonal boron nitride tunnel junctions

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Abstract

The conversion of an electrical signal to an optical signal with maximum bandwidth and practical on-chip integration is of fundamental interest. Here we present active optical antennas driven by inelastic electron tunneling. We have fabricated arrays of vertical coupled antennas in metal-insulator-metal arrangements based on electrically connected gold nano rods (GNR) and hexagonal boron nitride as insulating layer. By tuning the aspect ratio of the GNRs we shift the localized plasmon resonance of the antennas and adjust the emission wavelength.

1. Introduction

The conversion of an electrical signal to an optical signal with maximum bandwidth and practical on-chip integration is of fundamental interest. Therefore, light emission by inelastic tunneling has gained considerable interest, since it allows to construct an electrically driven plasmonic nano gap antenna. The electromagnetic coupling between resonant plasmonic oscillations of two closely spaced noble metal particles leads to a strongly enhanced optical near field in the gap between. Electron beam lithography or focussed Helium Ion Beam milling enables accurate control of the shape, aspect ratio, and gap size of the structures, which determines the spectral shape¹, position, and width of the plasmonic resonances². Many emerging nano-photonic technologies depend on the careful control of such localized resonances, including optical nano antennas for high-sensitivity sensors, nanoscale control of active devices³, and improved photovoltaic devices.

2. Discussion

However, achieving reproducible and stable experimental conditions with nanometer sized gaps in tunneling range remains a challenging task in high demand. We have fabricated arrays of vertical coupled antennas in metal-insulator-metal arrangements based on electrically connected gold nano rods (GNR) and hexagonal boron nitride as insulating layer. By tuning the aspect ratio of the GNRs we shift the localized plasmon resonance of the antennas and adjust the emission wavelength.

Figure 1: Shows the stacking of the device, starting with an ITO bottom electrode on glass. Followed by an array of GNRs, which is fabricated via E-beam lithography. Afterwards a few layers sheet of h-BN is transferred, and an evaporated Au top electrode complete the device. Electrons tunnel from the Au top electrode to the GNRs, where inelastic tunneling occurs and transfers energy to the plasmon, which later determines the emission wavelength.

3. Conclusions

The results discussed here show an on-chip solution of antenna modulated light emission from a tunneling junction approaching the ultimate size limits of an opto-electronic device, while the operating speed is only limited by the electron tunneling time. The reviewed concept represents a novel platform for ultra-small, fast, optically, and electronically switchable devices and could find applications in high-speed signal processing and optical telecommunications.

References


Excitons in nanophotonic landscapes: fluctuating, diffusing, annihilating

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Abstract

Excitons in atomically thin semiconductors are sensitive to their electronic and photonic environments. Here we present our experimental and theoretical results on the fluctuation, diffusion, and annihilation of excitons near nanostructures. Our results have implications for exciton-based sensors, single-photon sources based on 2D materials, and efficient and high-power light-emitting devices.

1. Excitons dynamics in nanophotonic landscapes

Excitons in two-dimensional semiconductors exhibit rich dynamics. Their fluorescence is sensitive to the nanoscopic environment. They are confined in the vertical direction while extending and diffusing along the atomically thin plane. Excitons can also interact with each other, notably to reduce light emission at high densities through exciton-exciton annihilation.

In this presentation, first, we will demonstrate that an atomically thin semiconductor can display substantial temporal fluctuations in fluorescence intensity influenced by its environment. We show blinking and flickering synchronized over monolayer domains tens of micrometers in size. We analyze the fluctuation statistics to draw analogies with blinking in conventional quantum dots.

Second, we will discuss strategies to increase the number of photons emitted by a 2D semiconductor based on nanophotonic enhancement. We study how exciton diffusion impacts fluorescence enhancement using nanophotonic structures. As mobile excitons diffuse through optical hotspots, the careful balance of diffusion constants and nanophotonic geometry can lead to enhanced or suppressed fluorescence. Finally, we theoretically investigate the effect of nanophotonic enhancement on exciton-exciton annihilation.

Our results open new vistas for nanoscale photonics and optoelectronics with atomically thin semiconductors. Controlling exciton dynamics in the form of fluctuations, diffusion, or annihilation has direct implications for stable single-photon sources, molecular sensors based on excitonic fluorescence, or high-power light-emitting devices.

Figure 1: Video frames of a monolayer semiconductor on a nanostructured substrate recorded in wide-field photoluminescence microscopy. Exciton fluctuations are visible as microscopic domains exhibit emission changes over time. The total crystal size approximately 50 × 100 μm
Light management at the nanoscale bioinspired by photosynthesis photonics.

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Abstract

Photosynthesis (PS) is arguably the most important energy harvesting process on Earth and, unsurprisingly, the research on how PS transforms light, water and CO₂ into chemical fuel have been widely investigated during the last few decades. In addition to this, PS molecular processes are not only a very interesting fundamental biochemical question but can also serve as inspiration towards so called artificial photosynthesis [1]. A variety of technological approaches have been proposed to mimic PS and obtain light powered water splitting, CO₂ capturing or biofuel production. However, whilst most efforts have been directed to understand and mimic molecular aspects of PS, its nanophotonic aspects have been widely overlook.

It was recently discovered that beyond the photochemistry of photosynthesis some organisms present intracellular nanostructures to manipulate light reaching the PS organelles at single cell level [2,3]. This is a demonstration that living organism can use nanophotonic principles for advanced light management at the nanoscale. And although many of the functionalities of such nanostructures are as yet unexplored, our studies suggest that they can range from the enhancement of light absorption to dynamic light reflectance or exciton propagation enhancement.

In this talk we will present different strategies to mimic the natural photonic properties of recently discovered photonic PS systems. We are using cost-effective micro- and nanofabrication methods to reproduce the phenomena of enhanced absorption and structural colour found in the leaves of some plants [2]. Such nanophotonic biomimetic approaches can work as a playground to better understand the natural system but also as inspiration for new strategies on light harvesting technologies. Moreover, and as an example of natural nanophotonics beyond light harvesting, we will show that the silica exoskeleton of some diatom microalgal species (Figure 1) contain high quality slab photonic crystals [4] that can be used as a naturally produced nanophotonic material in applications such as bio-sensing, opening the door to bioengineered nanophotonic devices.

Figure 1: Silicon dioxide photonic crystal slab produced by the microalgae Cosconodiscus granii as part of its exoskeleton[4]. Slab thickness is ≈ 1 µm. The pores form a square interconnected lattice with lattice constant a ≈ 280 nm.

References


Chiral Nanophotonics with Atomically Thin Semiconductors

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Abstract

Spin-valley polarization in atomically thin semiconductors opens a new perspective to explore optical chirality. Here we summarize our progress on the exploitation of 2D semiconductors as sources and probes for chiral nano-optics. We show how competing optical transitions in few-layer materials allow a high degree of circular polarization. Second, in order to enhance polarization, we design achiral nanophotonic resonators that satisfy the conditions needed for improving chiral light emission as a path towards efficient sources of spin-valley-polarized light.

1. Introduction

Two-dimensional semiconductors hold great promise for nanoscale photonics and optoelectronics. Based on robust excitons at room temperature (Figure 1), they exhibit strong light absorption [1] and emission [2] and they are easy to integrate into nanophotonic structures [3]. One of their most promising properties is spin-valley polarization. In atomically thin semiconductors such as monolayer MoS2, the spin and momentum direction of carriers can be locked. As a result, using circularly polarized light, we can populate carriers with a momentum direction that depends on the handedness of the optical excitation.

This degree of freedom, known as valley polarization, could be exploited to add a new dimension to information processing and optoelectronics.

More generally, the interaction of circularly polarized light with matter is the basis for chiroptical applications such as optical spin manipulation, molecular circular dichroism spectroscopy, or optical torques. Chiral optical fields can, therefore, address spins in condensed matter. Nanophotonic structures can assist in enhancing such chiral light-matter interaction.

The ideal valley-polarized material should exhibit high emission quantum efficiency together with high polarization. However, currently available transition metal dichalcogenides (TMDs) suffer from either low efficiency or low polarization. To enhance circularly polarized emission, in this presentation, we follow two different routes. First, we exploit the competition between different optical transitions in the band structure of few-layer materials to obtain high spin-valley polarization. Second, we design achiral nanophotonic resonators that satisfy the conditions needed for improving chiral light emission. We propose guidelines for enhancing spin-polarized emission with evanescent fields, which are incompatible with the requirements for enhanced molecular circular dichroism [4].

2. Spin-valley polarization in few-layer semiconductors

Using circularly polarized luminescence, we characterize spin-valley polarization through the degree of circular polarization of the emitted light. Indeed, materials such as WS2 have shown that they can support high degrees of spin polarization even at room temperature.

As a first route to increase polarization towards 100%, we investigate the impact of competing indirect transitions on the spin-valley polarization of few-layer tungsten-based dichalcogenides. As shown in Figure 1, WS2 bilayer excited with a laser energy close to excitonic resonance exhibits around 90% polarization. We compare different materials to explain the microscopic origin of such a high polarization arising from indirect transitions with intrinsically low quantum efficiency.
3. Chirality in evanescent fields

A second path to enhance spin-valley polarization and emission quantum efficiency is the exploitation of nanophotonic resonators tailored for spin-polarized light emission. Indeed, nanophotonic antennas can enhance optical intensity, but attention must be paid to preserve circular polarization in the near field as required for chiral light-matter interactions.

We will demonstrate the conditions needed for enhancing chiral fields near achiral nanoparticles arranged as metasurfaces for maximum chirality of the evanescent fields (Figure 2). To illustrate these conditions, we compare the performance of arrays of metal and dielectric nanodisks. By decomposing their intensity and chirality metrics into propagating and evanescent Fourier orders, we prove that maximal near-field enhancement of spin polarization is incompatible with enhanced interaction with chiral molecules (circular dichroism). Such a Fourier decomposition also allows us to predict a limit of maximum attainable circular dichroism in highly evanescent Fourier orders, in full agreement with full three-dimensional simulations [4].

4. Conclusions

We have explored two different paths to obtain highly efficient and polarized sources of circularly polarized light using atomically thin semiconductors. Our results could lead to efficient valley optoelectronic devices and show the potential of 2D semiconductors to study optical chirality at the nanoscale.

Figure 2: Nanophotonic resonators can enhance different chiral light-matter interactions such as spin polarization and circular dichroism. However, the maximization of one metric leads to poor performance for the other. For interaction with chiral molecules, using a Fourier decomposition into evanescent and propagating orders, we demonstrate a limit of maximum circular dichroism for evanescent waves.

References

Large scale fabrication of silicon Mie nanoresonators: an alternative to gold?

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Abstract

High index dielectric nanoparticles have been proposed for many different applications. The multiples optical properties of such called Mie resonators allowed us to question there use as an alternative to the metal, especially gold. Actually, the dipolar and quadupolar resonances, coupled with a strong near field can open new perspective in plasmonic uses. However, widespread utilization in practice also requires large-scale production methods for crystalline silicon nanoparticles, with engineered optical properties in a low-cost manner. Here, we demonstrate a facile, low-cost, and large-scale fabrication method of crystalline spherical silicon colloidal Mie resonators in water, using a blender as explained figure 1.

Figure 1: Fabrication of Silicon Mie resonator using a blender. The various diameters give a full range color spectrum scattering.

1. Introduction

Metallic nanoparticles are usually used for its scattering properties (optical antennas), near-field enhancement (SERS, MEF, coupling) and absorption (heat generation for medical issues, local chemistry). These three elementary bricks open a huge number of optical applications. But metallic nanoparticles have two strong limitations: the narrow optical range (need to change metal) and the corrosion for other metals than gold. We can so consider the high index dielectric nanoparticles as resonator for scattering and near-field enhancement applications. As metallic nanoparticles, the Mie resonators have electric dipolar (ED) and quadrupolar modes, but the positive dielectric permittivity allow them to generate magnetic dipolar (MD) and quadripolar modes as visible on the FDTD simulations figures 2. The position of these modes is only dependant on the size of the nanoparticles, and we are able to cover the full range visible spectrum by tuning the diameter. Mie resonators can so be consider as a good alternative to gold for plasmonic applications.

Figure 2: FDTD simulation on silicon nanoparticle. On left, the electric dipolar mode, on right, the magnetic dipolar mode.

2. Fabrication and applications

2.1. On substrates

Silicon Mie resonators on substrate can be fabricated using a femtolaser printing [1], but we propose a downsizing of the microelectronic well known techniques. These techniques are based on an etching (wet or dry) of a silicon wafer through a mask. Here we first demonstrate a wet etching of silicon weakly crystalline nano-layer by TMAH solution [2]. With this technique we can produce a wide size range nanoparticles, from 100nm to micron with very thin gap (down to 10 nm). But the clearance angle of the nanoparticles do not offer a very interesting optical proper-
ties. A dry etching is secondary developed using \(SF_6/O_2\) cycles alternated with \(O_2\) cycles [3]. This technique allow us to create nanocylinders with a very low clearance angle, then with a diameter range 70nm-210nm. We are able to cover the full visible range, and use them for nano-painting as visible figure 3.

![Figure 3: On the left, the original Mondrian painting Composition in red, yellow, blue and black, 1921 (59.5 x 59.5 cm\(^2\)). On the right, the nanopainting reduction (1:1200, 500 x 500 \(\mu\)m\(^2\)) made with silicon nanoparticles on glass](image)

**2.2. Colloidal Mie resonators**

The chemical synthesis of silicon Mie resonator is a huge challenge, because the native oxidation of the silicon into silica. One approach have been developed based on a annealing at high temperature of a rich silicon layer, followed by centrifugations in HF [4]. Even through this method produce colloidal Si nanoparticles, we propose a more efficient and safe alternative method. Our method is based on the grinding of silicon pellets in water using a simple blender (see figure 1) [5]. The obtained nanoparticles are polydisperse with an almost spherical shape and the diameters controlled in the range 80-200nm by a centrifugation process. Then the size distribution of silicon nanoparticles enables broad extinction from UV to near-infrared, confirmed by Mie theory when considering the size distribution in the calculations. Thanks to photolithographic and drop-cast deposition techniques to locate the position on a substrate of the colloidal nanoparticles, we experimentally demonstrate that the individual silicon nanoresonators show strong electric and magnetic Mie resonances in the visible range.

![Figure 4: Gamut chromatic diagrams of Silicon Mie resonators. Left on substrate, right in solution.](image)

**3. Color application**

Both techniques produce Silicon nanoparticles with a size range around 80-200nm. Both present a full visible spectrum scattering properties.

Figure 4 show the Gamut chromacity diagrams of the scattering of our silicon nanoparticles obtained with both techniques. We can observed than the nanoparticles made on substrates, even through they cover all the visible spectrum, lakes sparkles compared to our colloidal synthesis.

**4. Silicon equal to gold?**

Finally, might silicon Mie resonators replace gold in optical applications?

We perform FCS (Fluorescence correlation spectroscopy) on both silicon and gold nanodimers [6]. We demonstrate than, for fluorescence enhancement, Silicon dimer with 20 nm gap size is equal to gold, and even better for higher gape size.

**Acknowledgement**

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Doping zinc oxide nanohybrids for application in white light emitting diodes
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Abstract
We present a study concerning the effect of doping in inorganic/organic ZnO/PAAH (polyacrylic acid) nanohybrids. The doping atoms vary in their ionic size, electronic valence and concentration. Some of them have been are known to provide ZnO with magnetic properties. The effect on the optical properties of the ZnO nanoparticles of three different concentrations (0.1 %, 1 % and 5 %) of dopants is compared. The luminescent properties of the undoped and doped nanohybrids are reported.

Introduction
Zinc oxide is a common direct and wide band gap semiconducting material (3.37 eV at room temperature [1]), which has usually been used for multiple applications in the UV range [2]. A good crystalline quality of ZnO is obligatory to obtain a high luminescent efficiency, but the recombination on the inevitable intrinsic defects present in ZnO crystal lattice is competing with the excitonic emission, making the efficiency of these UV devices rather low. Though a tremendous effort has been devoted to reduce the presence of these undesirable defects, they can actually be attractive as they give rise to a wide range of light emission from blue to IR, especially at the nanoscale. They can be used as phosphors in white light emitting diodes (WLEDs) and in plus, they are rare-earth-free. This fact is non negligible, as it is China who assures 95 % of the global supply in rare earth elements today.

1. Sample preparation
The synthesis method used reproduces the one described in our previous study, given in [3]. It is based on the of diethyl zinc (ZnEt2) hydrolysis. 1.8 ml of a solution of diethyl zinc (15 wt%) in toluene is dropped wise in an aqueous solution containing 0.63 wt% of poly-acrylic acid, (PAAH).

During the synthesis process, the mixture is vigorously stirred all the time under inert atmosphere as ZnEt2 is pyrophoric. The ethane resulting from the hydrolysis is constantly evacuated. The reaction scheme is as follows:

\[ \text{ZnEt}_2 + \text{H}_2\text{O} \rightarrow \text{ZnO} + 2 \text{EtH} \]

2. Optical measurements
The optical properties of the nanoparticle samples were measured using the photoluminescence (PL) set up. It consists of a continuous wave laser emitting at 266 nm (power of 8 mW, model Crylas FQCW 266-10). The emission from the sample was collected with an optic fiber, then dispersed by a spectrometer (iHR Triax 320 Jobin-Yvon) and detected using a liquid-nitrogen cooled Si CCD detector. Since our main concern is to obtain materials with a high PL yield, the photoluminescence internal quantum efficiency (PL iQY) of our samples was also measured, using an integrating sphere with the same excitation and detection set up as for the PL studies.

3. Results and discussion
The obtained results confirm in the first place what was also observed in the literature, that increase in the dopant concentration leads to the quenching of the visible luminescence of ZnO nanostructures, whatever the fabrication process. In our case, for some doping atoms, a low doping concentration (0.1 %) can improve or at least permits to maintain the same PL iQY, when compared to non-doped ZnO nanopowders [4]. Finally, doping in
inorganic/organic ZnO/PAAH nanohybrids makes possible to tune the visible emission spectrum of this compound between 2.17 eV and 2.46 eV.

4. Conclusions

The degradation of photoluminescence internal quantum efficiency is not necessarily observed in then studied nanocomposites. At low doping concentration for some dopants with a small or comparable ionic radius to the one of Zn\(^{2+}\), PL IQY can be maintained or even improved, making it possible to tune the visible emission spectrum between 2.17 eV and 2.46 eV. This opens up the prospect of synthesizing phosphors without rare earths for white LEDs, whose spectrum can be rather easily tuned to fabricate warm or cold white light, by a chemical synthesis method having a low environmental impact.

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References

Light induced adaptation of structural colour and light absorption enhancement in photosynthetic photonic organelles

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Abstract

In this work, we communicate a theoretical investigation on a naturally occurring photonic crystal: the iridoplast, an adapted photosynthetic organelle found in plants living under low light conditions. Our numerical study suggests that these structures could be controlling the absorption and the reflectance of light in order to enhance photosynthetic activity. We model purely light dependent structural changes based on experimental reports. This could therefore have potential interest in other technological areas such as coloured solar cells.

1. Introduction

Nature has been using light as a source of energy for billions of years. A number of organelles have evolved in order to use light for photosynthetic purposes. Chloroplasts stand out the most due to their crucial role in energy harvesting for high plants.

A specialized case of chloroplasts, known as iridoplasts, have evolved into having a well-defined arrangement of the photosynthetic tissue forming a periodic multilayer structure, analogous to a Bragg mirror, which reflects strongly in the blue. Iridoplasts have been found in several species of deep shade plants, such as in the Begonia pavonina [1]. Their biological function is still debated but experimental evidence suggest that the photonic structure might enhance light absorption predominantly in the green [1] (figure 1) and simultaneously increase quantum yield when compared to traditional chloroplasts. Perhaps more interesting, iridoplasts show a light sensitive behaviour, shifting between high reflectance and no reflectance under low and high light conditions respectively.

The mechanism by which iridoplasts change optical properties at different light conditions remains unknown. In this paper we present numerical calculations that allows us to predict possible biological functionalities and optical properties of this natural photonic nanostructures.

2. Discussion

Using transfer matrix method (TMM) based simulations, we have calculated the variation in the optical response of iridoplasts under different morphological circumstances, always considering realistic scenarios of the biological system.

It is documented, although still debated, that the photosynthetic membranes within the chloroplast, known as thylakoids, will expand or contract depending on the light environment. Therefore, we have used the TMM to calculate the photonic response of the iridoplast under such light conditions. We varied the thicknesses of the layers in the iridoplast to mimic the natural system under different light conditions. These are expansions and contractions which have been found to exist in the layers of chloroplasts [2].

Figure 1: (Black) Absorption enhancement of the iridoplast as a function of wavelength compared to a traditional chloroplast, both under low light conditions, and (Red) absorption enhancement of the iridoplast under low light conditions compared to an iridoplast under high light conditions.

The results of our study are twofold. On the one hand, we find a clear redshift of the reflectance peak under the expansion of the thylakoid (figure 2). This expansion is equivalent to a larger period of the Bragg mirror and therefore consistent with the expected optical response of a multilayer photonic crystal. Our second result suggest that iridoplasts absorb more light under low light conditions than under high light (figure 1). These results point out that
Iridoplasts can tune their absorption by changing the photonic response of the multilayer according to the light environment. Finally, in this paper, we elaborate over the effect on the photonic response introduced by randomness in the thicknesses of the thylakoid layers. The natural system will not present the same thickness for all layers forming the iridoplast and therefore a realistic modelling of the natural photonic crystal should take into account this feature. We used experimental values reported earlier [1] to introduce random thicknesses in our model. Our results suggest that even considering a realistic amount of randomness in the thylakoid thickness the photonic response is still large enough to have a significant effect in the light harvesting of the natural system. From figure 2 it is also clear that there is a small angular dependence which is a consequence of this disorder considered.

![Figure 2: Angular dependent reflectance spectrum of iridoplasts under low light and under high light.](image)

This is an extraordinary case of photonics properties undertaking an important role in natural light harvesting. Understanding these natural systems can inspire us to develop technologies mainly related with light harvesting. An interesting field which might profit greatly from this is the rapidly developing one of coloured solar cells, which could developed into having dynamic colours.

3. Conclusions

With this work we show numerically which changes are expected in the photonic response of iridoplasts under morphological changes similar to those undertaken by chloroplasts under the same light conditions. Our results suggest that the expansion and contraction of certain layers could make the iridoplast more efficient in light absorption when under low light conditions whilst the enhancement of absorption due to the photonic structuration will be reduced under high light conditions due to the lattice expansion. In conclusion, these results further reinforce the idea that iridoplasts are photonic environments that have developed to self-adapt to different light conditions in order to enhance photosynthetic efficiency. Understanding these photonic properties will help us develop new approaches to light harvesting, such as coloured solar cells.

Acknowledgements

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References


Microscopic Study on Circular Dichroism Localized in Materials to Analyze Hierarchical Chirality in Various Scales

Tetsuya Narushima

Abstract
Circular dichroism (CD) has been utilized to analyze molecular chirality. These years, it has been reported that spatially extended chiral systems, such as crystals, molecular assemblies and nanostructures, also show CD activity. In order to explore properties of the CD activity and its physical origin, we developed a CD microscope and visualized spatial CD distribution observed in the chiral systems of metallic nanostructures, biological cells, and so forth.

1. Introduction
Measurement of circular dichroism (CD) has been utilized to analyze molecular chirality. Chiral structures can be also observed hierarchically in materials [1] or biological cells [2]. These years, optical activity of nanostructured materials distinct from that observed in the molecular scale attracts a lot of interest [3,4]. The novel optical activity originates from chiral interaction occurred at spatial scales comparable with or larger than optical wavelength. Chiroptical property of the larger chiral materials should be manipulated through artificially modifying their shape and composition. To design the optical activity and to explore microscopic origin of them, spatial information on the optical activity must be helpful. Therefore, we have developed two types of circular dichroism (CD) imaging system based on optical far-field and near-field detection.

2. Microscopic CD measurement
Microscopic imaging of CD is a direct method to measure the spatial distribution of CD signals. However, CD imaging has not been commonly employed, because considerable artifacts from linear dichroism (LD) of the sample arising from the conventional method of CD detection interfere in the CD signal, and prevent accurate CD detection.

Recently, we developed a CD microscope based on a novel polarization modulation method, which greatly suppresses the interference from LD, and achieved reliable CD imaging [5]. In the conventional method of CD detection, a photoelastic modulator (PEM) device is adopted to realize modulation between left- and right-circular polarizations (LCP and RCP) at the frequency of ~50 kHz. This circularly polarized light (CPL) modulation with the PEM device inherently involves linear polarization (LP) components in the output light beam, which leads to the LD artifact. Figure 1 shows an optical configuration of our new method of CPL modulation. Samples are alternately illuminated only with LCP and RCP beams with high polarization purity. The modulated CPL does not include LP component in principle, and thus commingling of the LD artifact should be much reduced.

Figure 1 Optical configuration of CPL modulation.

2.1. Far-field CD microscopy
To evaluate performance and characteristics of the developed a CD microscope with our new CPL modulation, an artificially-fabricated array of chiral gold nanostructures was used as a sample. Figure 2a and 2b show simultaneously-observed transmission and CD images, respectively. In the transmission image, strong extinction was observed as dark regions at the central positions of the individual nanostructure. In contrast, maximal CD spots were seen at the top, bottom, left and right sides of the
nanostructure in the CD image. The CD spots arranged in a configuration of 4-fold symmetry indicate that the microscopic CD imaging was not affected by the LD artifact. From the size of the CD spots, spatial resolution of the CD microscopy was estimated to be 300-400 nm. Sensitivity of the CD signal was $10^3$ level (in optical density unit), which was determined by measuring the standard sample with known absorbance. We thus realized reliable method of visualizing local CD distribution with a high CD sensitivity at a nearly diffraction limited spatial resolution.

2.2. Application of CD microscopy to biological sample

In biological research fields, observation of fluorescence from the target molecules such as protein is routinely made for tracking the positions of molecules. Various chiral structures hierarchically exist with dimensions from subnano- to micro-meter scales in biological systems. In addition to spatial distribution of the target molecules, optical activity signals and chirality of the molecules and molecular assemblies, such as DNA and chromosome, may provide invaluable information to reveal mechanisms of biological functions as well as expression of asymmetry on living organisms. We are currently attempting to adapt our CD microscope for researches toward those purposes. As a feasibility test toward biological application, intracellular structures of the root of an onion was observed. Figure 3 shows images of dye-stained onion cells at the mitotic stage. CD images of the intracellular structures were observed at different wavelengths. CD signal at chromosome region was negative for the CD image observed at 550 nm (Fig. 3b), while positive CD was seen for that at 600 nm (Fig. 3c). In other wavelengths (650 and 700 nm, not shown), the CD signal at the chromosome region was too small, although the cell walls were faintly recognized. Inversion of the sign of the CD signals (negative at 550 nm to positive at 600 nm) observed at the chromosome region may originate in specific chirality in some hierarchical structure. This result shows a potential of CD microscopy as a new bioimaging tool based on chirality. Further analyses combined with other conventional microscopic and spectroscopic techniques will give us novel methodologies which are indispensable for revealing the origin of observed local CD and biological functions.

![Figure 3](image)

**Figure 3** Optical transmission image (a) and CD images for division of onion root cells (b,c). Wavelengths for CD imaging were (b) 550 nm and (c) 600 nm.

2.3. For further spatial resolution: Near-field CD microscopy

The near-field response from the sample enables us to analyze chirality in materials with nanoscale resolution. We observed near-field CD images of plasmonic nanostructures with chiral shapes, and found that both positive and negative CD signals were localized even in the individual chiral nanostructures (Fig. 4). The local CD signals were two-orders of magnitude larger than macroscopically observed CD signal [6]. These near-field CD images were obtained with the conventional CPL modulation with the PEM device. By incorporating the present polarization modulation device, near-field CD microscopy with higher spatial resolution and reliability can be realized, and is currently under development.

3. Conclusions

Highly reliable CD microscopy free from LD artifact with high spatial resolution enables direct analyses of local chiroptical properties and handedness of nanomaterials and microparticles that may provide novel functions. The unique methodology must be also advantageous in investigation of hierarchical chirality in various scales typified with biological molecular systems. Visualization of chirality and its structural changes in time may provide vital information for understanding of intermolecular coupling and cooperation, which relates to functions of biological systems.

References

Ultrafast Spectroscopy and Imaging of Quantum Optical and Plasmonic Processes

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Abstract
There is a strong need for the ability to spatially resolve photoinduced processes in nanoscale structures, and to temporally resolve the evolution of energy flow in these structures. These materials can be particularly challenging for imaging due to issues with scattering and small sample volumes. Novel approaches to the time-resolved spectroscopy and imaging of quantum optical and plasmonic processes are described here.

1. Introduction
Ultrafast spectroscopy and imaging of nanostructures are typically performed in media such as homogeneous solutions or smooth optical films, in order to keep scattering to a minimum and to increase signal to noise of data collection. However, this is of course not the typical environment in which we hope to deploy nanoparticle systems for various applications in energy conversion, sensing, and biomedical applications. Once nanoparticles are deployed into biological systems, functional devices, or as environmental probes, the ability to truly understand their photophysical or photochemical function is greatly diminished. The presence of heterostructured interfaces, cellular systems, and general inhomogeneity of the local structure surrounding the particles makes advanced spectroscopies and imaging difficult or impossible. With this in mind, in this talk I describe new efforts to understand nanoparticle photo-induced processes of nanostructures through spatiotemporal visualization and characterization using ultrafast spectroscopy and optical microscopy. By undertaking this effort over a broad range of the electromagnetic spectrum, we seek to gain a complete view of energy flow and dissipation into the environment following photoexcitation at the nanoscale. In this way, an overall ability to sense nanoparticle function in scattering or otherwise challenging environments can be achieved. Of particular importance is a need to image with spatial and wave-vector specificity, in order to more fully understand the anisotropies of energy flow in complex, functioning systems (for example, the anisotropic flow of charge or energy across a nanostructured interface). Such spectroscopy and imaging are needed to fully understand the function of nanomaterial assemblies. I will also describe in the talk some of our new experimental capabilities, available to external users, in time-resolved spectroscopy and imaging.

2. Imaging light induced quantum optical and plasmonic processes
We describe efforts to perform time-resolved pump-probe imaging in highly scattering materials and over a broad spectral range. The experiments are intended to reveal the time-resolved spatial and spectral changes in technologically relevant materials. Our work is also designed to specifically reveal wavevector dependent, anisotropic energy flow in nanostructured materials, to reveal, for example, the flow of phonon/mechanical energy following photoexcitation. Efforts to perform imaging in Fourier space to more ideally visualize anisotropic processes and their temporal evolution are also described. The pump-probe efforts are primarily coupled to plasmonic processes. We also describe the effort to image quantum optical emission processes in perovskites and semiconductor nanoparticle emitters. This work builds on our recent work in time-resolved plasmonics and quantum emitters [1-4].

3. Conclusions
We report novel routes to time-resolved imaging of plasmonic and quantum optical processes in nanostructured materials. Potential applications to realistic systems for applications are described.

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References


Measuring the magnetic dipole transition of single nanorods by Fourier microscopy

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Abstract

Rare-earth ions can present optical transitions with significant magnetic dipole (MD) character that can be manipulated by the crystalline or molecular hosting environment. They are of strong interest for engineering light-matter interaction at the nanoscale with numerous applications in nanophotonics. We analyze in details the optical transition in individual and single crystalline rare-earth doped nanocrystals. We measure the MD orientation and demonstrate a 100% magnetic transition in our homemade synthesized single crystalline nanorods.

1. Introduction

Engineering optical magnetic dipole (MD) opens new class of designs such as metamaterials considering artificial MDs [1] or magnetic nano-optical antennas considering natural magnetic transitions observed in the trivalent lanthanide ions [2]. Since some emission lines are very sensitive to the local temperature, rare-earth doped nanocrystals have been used as temperature sensor scanned above an electronic circuit [3]. Luminescent nanocrystals are also considered as active probes for scanning near-field optical microscopy delivering a signal proportional to the local electric- [4], magnetic [5, 6] fields or density of states (LDOS) [7, 8, 9]. These luminescent nanoparticles constitute a family of versatile nanoprobes and engineering their emission lines would unlock the full potential of applications.

In this work, we investigate in details the ⁵D₀ → ⁷F₁ transition in Eu³⁺ ions that presents mainly a MD character. Several works considered randomly oriented emitters in solution or thin films and observe that the MD transition could present an electric dipole character [10, 11]. Differently, in rare-earth doped nanocrystals, the crystalline host matrix induces a crystal field splitting of the electronic sublevels and strongly polarized optical transitions occur [12]. We notably demonstrate that it is a fully MD transition. We measure the MD orientation and quantify the contribution of MD transitions towards the Stark sublevels resulting from the crystal field splitting.

2. Fourier microscopy of single crystalline NaYF₄:Eu³⁺ nanorods

Europium doped single crystalline NaYF₄:Eu³⁺ nanorods with the average diameter of 90 nm and length of 1500 nm are synthesized as described in Ref. [13] and randomly dispersed on a quartz substrate. To be sure that emission spectra are originated from nanorods, a confocal image is first acquired, see Fig. 1a), before acquiring polarized diagram emission Fig. 1b) or Fourier images (Fig. 1c).

The results obtained for several individual nanorods are summarized in Table 1. The dispersion of the angle measurements are small (standard deviation less than 2°). We emphasize that we fully explain the recorded Fourier images considering a fully magnetic transition but taking into account the contribution of the two MD transitions within the spectral range. In addition, Fourier imaging is performed with a high NA objective. The dipolar emission above the critical angle originates from the evanescent coupling into the substrate and the distance between the nanorod and the substrate should be considered as an additional fitting parameter in the model. We found an effective height of 59.6 nm. It represents the ponderation by the evanescent coupling over the rod height and can be used to extract information on the distance between the rod and the substrate.

Table 1: MD orientation deduced from Fourier images of single NaYF₄:Eu³⁺ nanorods. Due to the large width of the band pass filter (591.0-598.6 nm), two dipoles (MD2, MD3) are collected. The proportion of MD3 (noted p₃) and the distance z₀ to the substrate are also estimated.

<table>
<thead>
<tr>
<th>Rod</th>
<th>MD2</th>
<th>BP2</th>
<th>MD3</th>
<th>p₃</th>
<th>z₀ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>73.6°</td>
<td>36.2°</td>
<td>0.87</td>
<td>65.6</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>72.9°</td>
<td>35.1°</td>
<td>0.89</td>
<td>50.1</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>73.4°</td>
<td>36.6°</td>
<td>0.88</td>
<td>61.4</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>69.9°</td>
<td>35.3°</td>
<td>0.90</td>
<td>57.8</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>71.2°</td>
<td>36.9°</td>
<td>0.88</td>
<td>63.2</td>
<td></td>
</tr>
</tbody>
</table>
3. Conclusions

We have fully characterized the magnetic dipole moment associated to the $^5D_0 \rightarrow ^7F_1$ transition in individual NaYF$_4$:Eu$^{3+}$ nanocrystals by Fourier confocal microscopy. We observe a fully magnetic transition and we determine the orientation of the three MDs for the hyperfine levels originating from the crystal field degeneracy breaking. The measured MD orientations present very low dispersion from one rod to another. Such nanocrystals could be used for vectorial mapping of the magnetic field and LDOS near nanophotonics structures, notably metamaterials and nanoantennas. The sensitivity of the Fourier imaging with respect to the altitude of the rod is also of interest to calibrate near-field optical measurement.

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References

Broadband light beaming from a helical traveling-wave nanoantenna

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Abstract
Nanoantennas are appealing for their ability to directionally radiate light, with important implications in the optical detection of nanoscale objects. Based on the control of the resonant or dispersive properties of nanostructures, nanoantennas usually radiate light at a given direction over a narrow spectral bandwidth. Here, we show that a broadband light beaming can be obtained from an individual helical traveling-wave nanoantenna. We experimentally find an emerging light pointing towards the helix axis with a divergence half-angle smaller than 25° over a spectral range of 1.47 µm - 1.65 µm (limited by our laser bandwidth). Numerical simulations show that such a beaming property holds over a wavelength range spanning from 1.2 µm to 1.8 µm. Our nanoantenna thus offers a broadband subwavelength and efficient optical interface between the nanoscale and remote bulky light sources and detectors.

1. Introduction
Resonant nanoparticles and nano-apertures are currently used to concentrate light in nanoscale volumes. Such a strong confinement usually imposes highly diverging scattered light in free space, laying difficulties for the far-field detection of nanoscale objects. Light beaming from an individual nano-aperture is possible when the nanostructure is surrounded by a periodic grating [1], at the expense of an overall structure larger than the wavelength of light and a strongly wavelength-dependent radiation directionality. Alternative solutions of smaller footprint are based on the interference of the multipolar modes of an individual dielectric nanoparticle [2], or on near-field interactions in a plasmonic chain (Yagi-Uda nanoantennas [3]). Relying on optical resonances, such nanoantennas ensure directional radiation over a narrow spectral bandwidth.

Nonresonant optical antennas offer the prospect of a high directivity over a broad spectral range [4]. However, relying on dispersive propagating modes, these antennas lead to collimated radiations whose propagation direction is intrinsically wavelength-dependent. Moreover, they suffer from modest compactness with spatial footprints far exceeding the wavelength of light. An individual subwavelength nanoantenna capable of preserving a specific radiation direction over a broad spectral range is thus still lacking. In this paper, we present the beamforming properties of an individual aperture nanoantenna coupled to a subwavelength plasmonic helix. The resulting hybrid nanoantenna, called helical traveling-wave nanoantenna, is the extension to optics of the low-frequency helical antenna operating in the “axial mode” [5].

2. Results
Our helical nanoantenna is realized from a three-step fabrication process [6]. Figures 1(a) and (b) show the scanning electron microscope images of a resulting structure. The nanoantenna consists of a gold-coated carbon helix standing on a gold-coated glass substrate. A rectangle nano-aperture is milled in contact to the helix pedestal to locally feed the helix. The resulting hybrid nanoantenna is illuminated from the backside (the substrate). An optical image of the far-field radiation is shown in Fig. 1(c), featuring a single light spot. To investigate the directional property of the nanoantenna, the back focal plane (Fourier plane) of a 0.9 numerical aperture objective is imaged with a lens coupled to a camera. A coordinate transformation from the cartesian (x,y) to spherical (θ,φ) coordinates is then applied (see Fig. 1(a)).

Figure 1: (a, b) Scanning electron micrographs of the helical traveling-wave antenna. (a) side view, (b) top view. (c) Optical image of the hybrid nanoantenna illuminated from the backside of the substrate at
\( \lambda = 1.5 \) \( \mu \)m. Scale bar: 500 nm.

Figures 2 shows the angular radiation patterns at \( \lambda = 1.5 \) \( \mu \)m of a single rectangular nano-aperture in a gold film and of our hybrid helical nanoantenna, respectively. Identical nano-apertures are used in Fig. 2(a) and for building the helical nanoantenna (Fig. 2(b)). The radiation pattern of the nano-aperture alone shows a poor directionality with the presence of two off-axis lobes (showing maxima in the cross-sectional plane \( \phi = 0^\circ \)). Such a diagram refers to the dipolar properties of the nano-aperture. As a contrast, due to the existence of the plasmonic helical structure, the hybrid helical nanoantenna develops a highly directional and near axis-symmetrical beam pointing toward the direction \( \theta = 0^\circ \) (i.e., along the helix axis). The angular divergence of this main radiation lobe is less than 25° (half-width at half-maximum).

Figure 2: 2D radiation patterns of (a) the rectangular nano-aperture alone and (b) the same nano-aperture coupled to a plasmonic helix to form the helical traveling-wave nanoantenna. “NA” denotes the numerical aperture of the objective used to perform imaging.

Remarkably, we experimentally observe an axial beaming narrower than 25° (half width at half maximum) over a spectral range of 1.47-1.65 \( \mu \)m limited by our laser bandwidth. Numerical simulations using FDTD (Finite Difference Time Domain) further show that axial beaming occurs over a broader spectral bandwidth spanning from 1.2 \( \mu \)m to 1.8 \( \mu \)m.

3. Discussion

The directional radiation occurs with an individual structure of subwavelength lateral size (~\( \lambda /3 \)). Such a property is consistent with the “axial” mode of the radio-frequency helical antenna which inspired our plasmonic structure [5]. The resulting broadband beaming may thus reveal a non-resonant operation of our nanoantenna. The numerically predicted current distribution along the helical nanowire is in favor of such a non-resonant operation as no current nodes are observed along the helix. This also indicates a good impedance matching of the traveling mode of the helix to vacuum. Such an interpretation may differ from previous theoretical approaches of plasmonic nano-helices [7,8].

4. Conclusions

By extending the concept of helical antenna to the optical regime, we demonstrate broadband light beaming from an individual subwavelength plasmonic structure. Used in a non-resonant traveling-wave regime, the plasmonic helix can be seen as a compact, versatile and efficient interface between free-space propagating waves and confined light fields. This nanostructure provides new opportunities in the achievement of directional radiation from nanoscale objects and emitters, thus impacting many research domain including quantum optics, optical information processing, sensing, communications, and miniaturized displays.

Acknowledgements

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References

Extracting Meaning from the Analysis of Photoluminescence Decays of Colloidal Quantum Dots: What's in a Function?

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Abstract

We discuss functions for the description of the room-temperature photoluminescence decay of colloidal quantum dots that are practical to use and whose parameters have a straightforward physical meaning. We introduce a function that accounts for the long-time tails of the decays, highlighting processes that may be related to photoluminescence blinking, and which use can provide valuable information concerning the nature of the trap states involved in the recombination of charge carriers.

1. Introduction

The relaxation processes that shape the decay of band-edge excitons in colloidal semiconductor quantum dots (QDs) are the critical processes that determine the suitability of these materials for a potential application. Understanding the kinetics of photoluminescence (PL) decay of QDs is therefore of critical importance for their characterization and synthetic development. The dark-bright exciton model predicts that the kinetics of PL decay of an ensemble of nearly monodisperse II-VI QDs at room temperature should be practically single-exponential, with a characteristic lifetime, τ, equal to twice the intrinsic exciton radiative lifetime (bright exciton lifetime) [1-3]. This is rarely observed experimentally, even for QD ensembles with PL quantum yields approaching unity [4]. The decays are commonly approximated using a sum of exponential functions, which has physical meaning only in some cases [5], or a single exponential [6], ignoring the long-time tails of the decays. Nevertheless, we note that understanding the origin of the slow tails of the QD PL decays at room temperature is of particular importance, as these tails have been associated to charge detrapping processes thought to be involved in PL intermittency or blinking [7].

An example of a physically meaningful analysis of the room-temperature PL decay in terms of a sum of discrete exponential components has been reported for Langmuir-Blodgett-type films of QDs [5]. The measured PL decay in the films has been described by a sum of three exponentials where each component is directly associated with Förster resonance energy transfer (FRET) from a donor QD to acceptor QDs grouped in the first three “shells” surrounding the donor, with each shell defined according to its distance from the central QD donor. Without an underlying physical model, however, the choice of the number of exponentials is to a large extent arbitrary because the recovery of rate distributions from experimental decay curves is an ill-posed problem (that is, there will be many different rate distributions that could describe equally well the corresponding decay curve). This has led us to search for models for the description of the PL decay kinetics of QD systems at room temperature that are at the same time physically meaningful and practical to use.

2. Stretched exponential PL decay kinetics

We have shown [3,8] that the use of the stretched exponential (Kohlrausch) function, in the form derived by Förster from realistic models of luminescence quenching, allows resolving the decay into an exponential component, characterizing the QD intrinsic radiative and non-radiative processes, and a non-exponential component, due to additional channels of energy relaxation - FRET or FRET-type mechanisms (Dexter). This function describes the PL decay of the QD ensemble with three adjustable parameters: time constant, τ (directly related to the bright exciton lifetime as mentioned above and which may be estimated theoretically), a constant directly proportional to the concentration of acceptor species and the Förster radius, and the stretching parameter (stretching exponent), which gives valuable indication about the specific mechanism of PL quenching in the system. In particular, we have illustrated how PL decay can be understood in terms of the occurrence of FRET, assuming that the role of acceptors of photoexcitation energy is played by high-frequency anharmonic molecular vibrations in the environment of the QDs that act as donors [3].

3. PL decay kinetics taking into account reversible trapping of excited charges

We have presented a new function for the description of the non-exponential QD PL decay kinetics at room temperature that accounts for the long-time tails of the decays [9,10]. The underlying model we propose is as follows. A QD at room temperature is regarded as a two-level system, a
ground state and an excited emissive (bright) state. The bright state decays radiatively with a rate $1/\tau$. The charges photogenerated in the QDs can be trapped by $N$ identical electron (or hole) traps with a finite average rate constant for electron (or hole) trapping, $k_i$. The assumption of an average rate constant for charge trapping is made to limit the number of free parameters in the model. The trapped electron (or hole) can be detrapped with a rate constant $k_2$ ($k_1$ to $k_2$). We consider that the decay rate of the trap state, $1/\tau_{\text{trap}}$, is negligible when compared to $k_2$, that is, $1/\tau_{\text{trap}} \ll k_2$. We assume that $N$ is different for each QD in the ensemble and that the distribution of traps is governed by a Poisson distribution. The normalized PL decay kinetics of the QD ensemble is then a function of four adjustable parameters: time constant, $\tau$, trapping and detrapping rate constants, $k_1$ and $k_2$, and average number of traps per QD in the ensemble, $N$ [9,10]. The principle of detailed balance allows us to estimate the energy difference between the electron (or hole) and the trap state levels ($\Delta E_{\text{trap}}$) using the rate constants $k_1$ and $k_2$ obtained from fitting the function to the PL decays [9,10]. The use of this function to fit the PL decays of drop-cast films of CdSe/ZnS QDs has given values of $\tau$, $k_1$, and $N$ in good agreement with those reported in the literature [2,7,8]. An example of the trap depths obtained from the analysis of the spectrally-resolved decays is shown in Fig. 1.

This analysis can also provide valuable information concerning the nature of the trap states involved in the recombination of the photogenerated charge carriers. In particular, we believe we have found evidence that allows us to distinguish between surface states and intrinsic gap states as charge traps in the nanosecond timescale.

4. Conclusions

Our work elaborates on the fundamental understanding of the mechanisms of charge carrier dynamics in QDs. We present functions for the description of the QD PL decay kinetics at room temperature with physically meaningful parameters. A function that takes into account the long-time tails of the decays highlights processes that may be related to PL blinking. This function should be applicable not only to QDs of different shape [11] and composition, but as well to hybrid QD structures and materials beyond inorganic semiconductors.

References


Optically Active Nanostructures

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Abstract
We present advances in the development of various optically active nanomaterials. We discuss the main approaches to induce optical activity in nanomaterials, including: the synthesis of nanomaterials in the presence of chiral ligands, post-synthetic capping of achiral nanostructures with chiral molecules, presence of chiral defects and even simple stirring of achiral anisotropic colloidal nanostructures. Most of the optically active nanostructures demonstrate strong unique circular and linear dichroism responses and very interesting structural morphologies.

1. Introduction
Knowledge of the fundamental concepts relevant to optical activity in nanosystems is very important for further advancement of nanoscience and nanotechnology in general. Over the past years, the use of stereospecific chiral stabilising molecules has opened a new avenue to the area of optically active nanomaterials research [1-7]. Optically active nanomaterials are of high interest from both theoretical and technological points of view as they are promising candidates for a range of potential applications. Here we present some advances in the development of various optically active photonic nanomaterials. We discuss the main approaches to induce optical activity in nanomaterials, including: the synthesis of nanomaterials in the presence of chiral ligands, post-synthetic capping of achiral nanostructures with chiral molecules, presence of chiral defects and even simple stirring of achiral anisotropic colloidal nanostructures. We consider structure-property relations and investigate the influence of the concentration of chiral ligands and their binding modes upon the optically active colloidal nanocrystals and corresponding circular dichroism signals. Finally, we provide an outlook of the corresponding potential applications of selected optically active nanomaterials.

2. Results and Discussion
We report an investigation of the effect of chiral l-cysteine ligands (hereafter referred simply as Cys) concentration and binding mode on the CD intensity of the CdSe/CdS QDs, which were prepared by an exchange of achiral organic ligands with chiral cysteine (Cys) ligands. We have found that the dependence of QD CD signal intensity on Cys concentration is non-linear; initially the CD signal peak intensity increases with Cys concentration, followed by a decrease when a further excess of ligands is added. Moreover, CD intensity changes dramatically depending on ligand concentration, with up to one order of magnitude, which makes it one of the key factors that should be taken into account during the investigation of chiroptical properties of nanoparticles. By using NMR and FTIR spectroscopy and density functional theory (DFT) calculations, we have shown that, while at low concentrations Cys ligands are bound to the QD surface in a tridentate coordination, an increase of the Cys concentration switches the coordination trend towards bidentate binding modes. DFT approach has enabled us to quantitatively assess the stabilization of the Cys ligands via non-covalent interactions at different ligand concentrations and to clearly pinpoint these interactions. The other optically active nanomaterials include noble metal, titanium dioxide, molybdenum disulfide and various calcium carbonate based hybrid structures (Figure 1).

Figure 1: SEM images of calcium carbonate helices.

3. Conclusions and outlook
We believe these studies are of great interest as they provide a fundamental understanding of chiroptical phenomena at the nanoscale, by considering chiral ligand concentrations, ligand-ligand interactions and their
binding modes at the nanocrystal surfaces. In overall, optically active nanostructures present a great interest for science and technology due potential applications such as CD spectroscopy, optical sensing, metamaterials and nanophotonics.

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References


3D-Printed Terahertz Resonant Nanocones

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Abstract: Arrays of gold-coated 3D-printed nanocones resonating in the terahertz frequency range are investigated.

Planar 2D nanoantennas (NAs) over transparent substrates are well-known devices capable of concentrating free-space radiation well beyond the diffraction limit, leading to extreme local electric field values at the NA extremities. Recently, this feature has been successfully exploited to drive high-field phenomena in the terahertz (THz) frequency range (0.1–10 THz), such as THz induced electroluminescence \cite{1} and impact ionization \cite{2} in semiconductors, as well as THz-field-induced electron emission \cite{3}. Regarding the latter, however, the close presence of the substrate as well as the direction of the resonating electric field limit the effective use of planar NAs as electron emitters. In this work, we report on an extensive investigation of arrays of 3D-printed resonant THz nanocones (NCs). In particular, we have first optimized their design via numerical simulations to achieve a monopole resonance centered at around 1 THz. The collective electromagnetic response of the array has also been engineered, in order to obtain a constructive interference between the scattered light from the individual NCs (through the exploitation of a “lattice mode” \cite{4}), which finally results in a higher local field enhancement. Such arrays have been fabricated via a high-resolution 3D printing technology (Nanoscribe) based on two-photon absorption in a polymer material, and a subsequent evaporation of a 200-nm-thick gold layer. All the fabricated NCs present heights of tens of μm, an aspect ratio of 1/10 (base diameter/height) and a tip radius of curvature of 150 nm, determined by the maximum resolution of the fabrication technique. Finally, the THz response of the NC arrays has been characterized via a standard time domain spectroscopy setup, showing a good agreement with the results of numerical simulations. The distinctive features provided by these arrays make them an interesting platform to be combined with intense THz pulses for field-driven emission of ultrafast electron bunches. Details concerning experiments in this regard will be presented on-site.

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Photoelectrochemical Methanol Oxidation under Visible and UV Excitation of TiO$_2$-supported TiN and ZrN Plasmonic Nanoparticles

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Abstract

Combined experimental and computational approaches are used to optimize the performance of TiO$_2$-supported TiN and ZrN nanoparticles towards photoelectrochemical methanol oxidation. Issues leading to performance losses are analyzed and mitigation strategies are proposed.

1. Introduction

TiN and ZrN nanoparticles (NPs) are an emerging class of plasmonic materials that can be successfully used for harvesting energy of visible light in order to drive chemical reactions on the photocatalyst surface [1]. These refractory NPs effectively absorb light over $\lambda$ = 450-1200 nm, covering most of the solar spectrum. Both TiN and ZrN have the optical apparence of gold, but with the advantages of thermal stability, corrosion resistance and low cost. Previous theoretical and experimental research has shown that TiN does not exhibit as strong of a plasmonic resonance as gold (broader response, sample variability due to defect-dependent metallicity) [2,3]. ZrN is expected to be a promising plasmonic material, with a sharp blue-shifted local surface plasmon resonance (LSPR) in comparison to TiN [2]. Indeed, this theoretical prediction was verified by observation of a sharp plasmonic maximum for ZrN NPs decorated by a thin layer of SiN [4]. However, ZrN NPs appear to be less chemically inert owing to zirconium’s strong affinity for oxygen. A layer of dielectric ZrO$_2$ forms on the surface of ZrN NPs even in the presence of trace oxygen. The oxide layer has a detrimental effect on the LSPR, leading to its broadening and red-shifting [4].

Herein both experimental and computational approaches are used in order to optimize the performance of TiO$_2$-supported TiN and ZrN NPs towards photoelectrochemical CH$_3$OH oxidation under visible excitation. UV excitation is utilized in order to provide complementary information on the interaction between photogenerated carriers at the plasmonic NP/semiconductor interface.

2. Experimental

2.1. Synthesis and Characterization

ZrN NPs were synthesized by ammonolysis of Zr(NMe$_2$)$_4$, and all manipulations were done in a drybox in an Ar atmosphere or on a vacuum line. Clean Zr(NMe$_2$)$_4$ was prepared following a protocol from the literature [4]. A portion of the Zr(NMe$_2$)$_4$ (1.28 g, 4.78 mmol) was introduced into a reaction bulb charged with heptane and 21.6 mmol NH$_3$ was condensed into the bulb at 77K. The mixture was stirred at room temperature for 24 h and then at 80 °C for another 24 h period. Solids were isolated by filtration. The solid was loaded into an alumina boat, inserted into a furnace, and heated under NH$_3$ flow first at 250 °C for 15 min, and then at 900 °C for 2.5 h. It was then cooled under N$_2$ flow once temperature dropped to 500 °C. A mostly black powder was isolated. Crystallite size was 11 nm, as determined by analysis of PXRD peaks. Larger 17 nm ZrN NPs were obtained by heat-treatment of the same precursor at 1050 °C.

Following the synthesis of ZrN NPs, the ZrN and commercial TiN (PlasmaChem, 30 nm) NPs were dispersed onto a P25 TiO$_2$ matrix via the sonochemically mediated mixing of the transition metal nitride and TiO$_2$: NPs in 50:50 (v/v) H$_2$O:ethanol mixture overnight. The resulting photocatalysts contained 0.5 - 5 wt. % loadings of TiN and ZrN on TiO$_2$. The ZrN/TiO$_2$, TiN/TiO$_2$ and bare TiO$_2$: films for PE experiments were prepared by drop-casting 60 µL of ink comprising 20 mg of the photocatalyst, 30 µl of 5 wt% Nafion solution (Ion Power), 2.96 ml H$_2$O and 0.74 ml isopropanol, on FTO slide (coated surface area of 0.385 cm$^2$). Experiments were conducted in a three-electrode photoelectrochemical cell. The photocatalyst films deposited on FTO-coated glass substrates served as working electrodes, while Pt foil and Ag/AgCl in 3 M NaCl (BioLogic, Inc) were used as counter and reference electrodes, respectively.
2.2. Theoretical modeling

For this project, we performed both electromagnetic and quantum mechanical calculations. Using COMSOL and DDA, we computed both TiN and ZrN NPs. Our simulations of these NPs in solution and on a substrate are in agreement with experiments. The NPs embedded into the TiO$_2$ matrix show red shifted LSPRs due to the dielectric screening effect, as expected. Along with the classical electromagnetic calculations, we computed the generation rates of hot-carriers which have a sufficient energy to surmount the interfacial barrier using the quantum formalism [5]. Our classical and quantum calculations were used to interpret the optical and photoelectrochemical data.

3. Results and Discussion

Figure 1 compares experimental and theoretical extinctions of 20 nm TiN and 17 nm ZrN NPs in H$_2$O.

![Figure 1: Experimental (top) and computed (bottom) extinctions of 20 nm TiN and 17 nm ZrN NPs in H$_2$O.](image)

Although the photocurrent of ZrN/TiO$_2$ exceeds that of TiN/TiO$_2$, the reaction occurs on oxidized ZrN surface that adversely affect the reactions rate.

![Figure 2: Photocurrent of CH$_3$OH oxidation on thin films of ZrN/TiO$_2$ and TiN/TiO$_2$ photocatalysts under broadband visible excitation. 70 mW/cm$^2$ power](image)

In the presentation, we will discuss the effects of plasmonic NPs loading on photocatalyst activity, determine the origin of photocurrent enhancement and conduct thorough theoretical analysis of observed experimental phenomena.

4. Conclusions

ZrN/TiO$_2$ exhibit greater photocurrent enhancement compared TiN/TiO$_2$ for photoelectrochemical CH$_3$OH oxidation under visible excitation. However, the performance of the former photocatalyst can likely be further improved by using a metallic shell that would protect the ZrN core from oxidation. Another way to utilize the promising plasmonic properties of ZrN NPs would be to apply them for reduction reactions, coupled to a p-type semiconductor. Under reducing conditions, ZrN NPs must be protected from deleterious oxidation.

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References

Photo-thermoelectric Conversion of Plasmonic Nanohole Array

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Abstract

Plasmonic photo-thermoelectric conversion offers an alternative photoelectric conversion that is not restricted by semiconductor bandgaps. Here, we report a plasmonic photodetector consisting of an ultra-thin silver film with nanohole array, whose photodetection mechanism is based on thermoelectric conversion triggered by plasmonic local heating. The contribution of plasmonic local heating to thermoelectric conversion is verified experimentally and numerically, in order to discuss the mechanisms governing light detection. This plasmonic photo-thermoelectric conversion will be available for improving the power conversion of thermoelectric device by creating thermal gradients across the device.

1. Introduction

Photodetection by semiconductors originates from a photocurrent flow associated with electron–hole pair generation via light absorption. The absorption band is strictly limited by the value of the semiconductor bandgap, meaning that the response wavelength range for a semiconductor photodetector is determined by its bandgap. Meanwhile, we demonstrated a plasmonic photodetection driven by thermoelectric conversion – an alternative approach for photodetection - triggered by plasmonic local heating [1]. Our device consisted of a thin film of a thermoelectric material embedded with plasmonic atoms that generated plasmonic local heating and created a thermal gradient inside the film as a consequence of light detection by absorption, resulting in Seebeck voltage generation.

In fact, similar light detection via thermoelectric conversion can be realized by using a conductive single nanofilm that includes plasmonic couplers. In order to demonstrate a photodetection by the patterned conductive nanomaterials as practical photodetectors, we fabricated an ultra-thin silver (Ag) film punctuated by a nanohole array and examined its potential for plasmonic photodetection via thermoelectric conversion. In addition, we verified the amount of plasmonic local heating contributing to photodetection experimentally and numerically and compared this with the results of thermoelectric simulations to discuss its mechanism of photodetection.

2. Experimental

Figure 1(a) shows a schematic of an Ag thin-film photodetector with nanoholes fabricated on a substrate. A positive resist film with a thickness of 216 nm was prepared on a glass substrate by spin-coating. A pattern of nanohole was fabricated over an area of 500 x 500 µm² by electron beam lithography. An Ag thin film (40-nm thickness, 2.0-mm width, and 6.0-mm length) was deposited on the resist film. To carry out thermoelectrical testing of the nanohole-array Ag device, and area encompassing the nanohole pattern was irradiated with a diode laser. The photocurrent generated in the Ag thin film was measured using a digital multimeter.

Figure 1: Ag thin-film detector concept and nanostructure. (a) Schematic of the Ag thin-film photodetector; (b) Top-view SEM images of periodic plasmonic nanohole arrays.

3. Results and Discussion

3.1. Optical and electrical properties of Ag thin film with nanoholes

Figure 2 shows an extinction spectrum of the Ag nanohole array with a periodicity of 300 nm and a hole diameter of (192 ± 3.22) nm. The extinction peak is observed at 687 nm, indicating excitation of surface plasmon polaritons on the Ag nanohole array. The maximum EQE was observed at a wavelength of 690 nm, and the EQEs at other wavelengths were in the range of 1.8 to 2.2 x 10⁻³%. The wavelength dependence of the EQEs was similar to the extinction spectra of the Ag nanoholes. In contrast, illumination of the Ag film in an area away from the nanohole resulted in a maximum EQE of 6.1 x 10⁻⁴%, and no significant wavelength dependence was observed (Figure 2, blue triangles). These results suggest that light illumination on the nanoholes...
excites surface plasmon polaritons, leading to plasmonic local heating as a consequence of plasmon loss.

Figure 2: Plasmonic nanohole array extinction spectra and quantum efficiencies. Measured spectra for the arrays with periodicities of 300 nm. Measured external quantum efficiencies of plasmonic photo-thermoelectric conversion, for illuminations of the nanohole array (red circles) and for illumination of the Ag film as a reference position (blue triangles), are also plotted.

3.2. Quantification of Plasmonic local heating

We calculated the plasmonic local heating generated at the Ag nanoholes by using the COMSOL software package, including its heat transfer module. Since plasmonic local heating occurs as a result of the Joule effect, the heat power density \( q \) can be calculated using Equation (1).

\[
q(\mathbf{r}) = \frac{\omega}{2} \text{Im}(\varepsilon(\omega)) \varepsilon_0 |\mathbf{E}(\mathbf{r})|^2
\]  

where \( \varepsilon_0 \) is the vacuum permittivity, \( \varepsilon(\omega) \) is the relative permittivity of the material, and \( |\mathbf{E}(\mathbf{r})|^2 \) is the intensity of the electric field. Figure 3 shows a cross-sectional SEM image beside the modeled electric field distribution, for the same view of the Ag nanohole.

Figure 3: Electric field enhancement produced by plasmonic local heating. Cross-sectional view of nanohole: (a) SEM image; (b) Electric field distribution.

Heat transfer in a system can be described by a conventional heat transfer expression [2],

\[
\rho(\mathbf{r})c(\mathbf{r}) \frac{\partial T(\mathbf{r})}{\partial t} = \nabla k(\mathbf{r}) \nabla T(\mathbf{r}) + q(\mathbf{r})
\]

where \( T(\mathbf{r}) \) is a temperature, \( \rho(\mathbf{r}) \) is the mass density, \( c(\mathbf{r}) \) is specific heat, and \( k(\mathbf{r}) \) is thermal conductivity. Govorov et al. reported that temperature increases for periodic plasmonic nanoparticles cannot be estimated by considering the nanoparticles individually [3]. We calculated the local heating temperatures produced upon changing the unit numbers of nanoholes from 1 to 49. As the unit number increases, the amount of plasmonic local heating increases because of a rise in the external temperature generated by the neighboring nanoholes [4]. Figure 4 shows a logarithmic fit of plasmonic local temperature versus the number of nanohole units in the array. The fitted-data curve is expressed analytically in by Equation (3).

\[
y = 0.9171\ln(x) + 1.239
\]

As the number of nanoholes included in an illumination spot is \( 4.27 \times 10^4 \), the estimated plasmonic local heating temperature at the illumination spot is 11.0 K.

Figure 4: Dependence of plasmonic local heating on the numbers of nanohole. Calculated local heating temperatures (red circles) as a function of the numbers of nanohole in array, from a simulation model. The dashed line indicates a logarithmic fit to the data.

On the other hand, we estimated the amount of plasmonic local heating generated at the Ag nanohole arrays, experimentally. The experimental data revealed that plasmonic local heating of 4.61 K was generated, which is one half of that estimated from the calculation. It should be noted that our calculation technique generated a relatively good estimation of the plasmonic local heating temperature for the nanoholes, which contributes to the thermoelectric conversion process.

4. Conclusions

A plasmonic photodetector consisting of an Ag thin-film with a nanohole array patterns was fabricated and investigated. The photodetection mechanism was examined by verifying the amount of the plasmonic local heating, using both experimental and numerical methods. This plasmonic photo-thermoelectric conversion, an alternative photoelectric conversion, will be available for improving the power conversion of thermoelectric device by creating thermal gradients across the device [5,6]. The results will be shown in a presentation.

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References

Accelerated Foerster-Type Nonradiative Energy Transfer of Semiconductor Nanocrystals

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Abstract

We present a review of accelerated nonradiative energy transfer employing semiconductor nanocrystals by using either the plasmonic effect or the dimensionality effect. We start with the enhanced Foerster-type resonance energy transfer (FRET) accelerated via selective plasmon mediation between NCs. Next, we present FRET accelerated via dimensionality and show the ultrafast exciton transfer from a thin film of CdSe/CdS nanoplatelets to a MoS2 monolayer. Our findings indicate that such accelerated FRET of NCs holds great promise for optical sensing and photodetection.

1. Introduction

The Foerster-type nonradiative energy transfer (FRET) is an important proximity effect that strongly modifies the emission kinetics of nano-emitters serving as donors and acceptors. In semiconductor nanocrystals (NCs), such as colloidal quantum dots (QDs) and nanoplatelets (NPLs), FRET takes place by long-range dipole-dipole coupling between the donor and the acceptor NCs. However, large NCs size decreases FRET rates. To overcome this limitation, the local electric field enhancement from a localized surface plasmon (LSP) near a metal nanoparticle (MNP) and the dimensionality effect coming from the change in the exciton confinement due to the difference in the NCs geometry, is used to boost FRET rates.

2. Discussion

We investigate the plasmon-enhanced FRET by selectively generating plasmon-exciton coupling to either: a) only the donor NCs, b) only the acceptor NCs, and c) the donor-acceptor NCs of the energy transfer pairs using layered constructs of MNPs and NCs. We analyze the consequent modifications in NCs emission kinetics under plasmon-coupled FRET conditions and systematically investigate the cascaded energy transfer mechanisms through steady-state and time-resolved photoluminescence measurements, along with lifetime and decay rate analyses. We show that plasmon-enhanced FRET at the only donor site is not the same as plasmon-enhanced FRET at the only acceptor site, which means that the cascading order does matter. For instance, when the plasmon is coupled only to the donor, we observe a 1.93 fold emission enhancement of the acceptor NCs as compare to only FRET mechanisms (Fig. 1). In the case of the donor-acceptor plasmon-exciton coupling, we used a photovoltaic controlled device, which couples MNPs to the donor–acceptor NCs and enhances exciton transfer from the donor to the acceptor NCs during the device’s operation. We analyzed the changes in NCs emission under the localized surface plasmon FRET condition and systematically studied the enhancement in energy-transfer rate within our structures. Here, the amplitude-average PL lifetime of the donor NCs layer decreases from 10.08 ns to 7.52 ns in the donor-acceptor bilayer structure, compared to the reference only donor structure. Similarly, the amplitude-average PL lifetime of the donor NCs layer further decreases from 7.52 ns to 3.13 ns in the donor–Au MNP-acceptor trilayer structure compared to the donor-acceptor bilayer, indicating strong energy transfer (Fig. 2). The experimental measurements reveal that the LSP-enhanced FRET rate is 22 ns⁻¹, which is much faster than the FRET rate only of 0.03 ns⁻¹. Lastly, we investigate FRET for the case of CdSe/CdS NPLs to MoS2 monolayer separate by a layer of Al₂O₃ with a thickness (d) going from 1 nm to 40 nm. Here, FRET takes place 7- to 88-fold faster than the Auger recombination in these NPLs for separation distances (d) going from 5 to 1 nm. Our measurement reveals that the FRET rate scale with the separation distance as d⁻² with a Foerster radius of ~33 nm and ultrafast rates (Fig. 3). For instance, when Al₂O₃ thickness is less than 5 nm, FRET occurs on an ultrafast time scale of 3.73-46.40 ps. These ultrafast FRET times overcome the Auger recombination process in NPLs (150–500 ps for CdSe NPLs), making these hybrid FRET structures potentially interesting for reducing optical gain threshold in lasing systems and increasing charge extraction performance in multiexcitonic photovoltaics.
Figure 1: (a) Time-resolved photoluminescence decay curves of the quantum dots under different plasmonic and/or FRET conditions collected at the donor emission wavelength. (b) Photoluminescence spectra of the D (green), A (dash-orange), D-A FRET pair (red), FRET for the D-A pair when only the donor is coupled to MNP (brown), and FRET for the D-A pair when only the acceptor is coupled to MNP (brown).

Figure 2: (a) Time-resolved photoluminescence decay curves of the NC layers under different plasmonic and/or FRET conditions collected at the donor emission wavelength (550 nm) and numerical simulations showed that the plasmon-enhanced FRET device perfume better than the FRET-based device only due to the strong plasmon-exciton coupling in the donor-Au MNPs-acceptor layered. Finally, for the case of CdSe/CdS NPLs and MoS₂, we show (1) a near-unity (99.88%) FRET efficiency with a Forster radius of ~33 nm and (2) a FRET distance dependency of d⁻² due to the layer-to-layer dipole coupling between the donor and acceptor. These results suggest that accelerated FRET of NCs holds great promise for use in optical sensing and photodetection.

3. Conclusions

We show that plasmon coupling enhances FRET depending on the position of the plasmon coupling. Our experimental and numerical results show that the donor FRET rate with plasmon coupled to the acceptor is significantly larger than that without plasmon coupling. In the case of donor-acceptor plasmon-exciton coupling, photovoltaic device, Au-MNP-assisted FRET resulted in a significant increase in the population of photogenerated excitons, enhancing the device’s sensitivity. The experimental data and numerical simulations showed that the plasmon-enhanced FRET device perfume better than the FRET-based device only due to the strong plasmon-exciton coupling in the donor-Au MNPs-acceptor layered. Finally, for the case of CdSe/CdS NPLs and MoS₂, we show (1) a near-unity (99.88%) FRET efficiency with a Forster radius of ~33 nm and (2) a FRET distance dependency of d⁻² due to the layer-to-layer dipole coupling between the donor and acceptor. These results suggest that accelerated FRET of NCs holds great promise for use in optical sensing and photodetection.

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References

Enhancing second-harmonic generation using dipolar-parity modes in non-planar plasmonic nanocavities

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Abstract
Efficient optical nonlinear sources at the nanoscale are important for the development of photonic circuitry, quantum optics, and biosensing. In this work, we use metal-insulator-metal nanocavities to demonstrate strong second harmonic generation in nanoscale plasmonic cavities. We show that in contrary to the common belief, double-resonant cavities can designed with dipolar-type modes for both fundamental and emission resonances.

1. Introduction
Plasmonic systems have been used extensively to boost the nonlinear signal generation at the nanoscale, such as second harmonic generation (SHG), third harmonic generation and four-wave mixing. However, high efficiencies of frequency conversion for realistic applications remain a challenge. Metal-insulator-metal (MIM) plasmonic nanocavities are good candidates for strongly concentrating the fields at the nanoscale to enhance the optical nonlinearities. However, MIM cavities typically suffer from the requirement to have a quadrupolar resonance at the emission wavelength.

2. Results and Discussion
In this work, we introduce non-planar MIM nanocavities with a nonlinear spacer that can strongly enhance the second-harmonic generation, despite having fundamental and emission modes of the same parity \cite{1}. Our experimental and numerical results indicate that the enhancement is due to the non-planar design of the cavities and the bulk nonlinearity of the spacer layer.

We show that multi-resonant MIM cavities can be utilized to enhance the SHG at the nanoscale. It is typically challenging to design MIM cavities with quadrupolar mode matching of the double wavelength of the fundamental modes. Here, we use third-order modes to match the SHG wavelength. By using the bulk nonlinearity of the spacer layer, we show that such systems can exhibit strong far-field SHG, despite having the same parity for both excitation and emission modes. The resulting efficient SHG nanosource will pave the way for novel integrated photonic applications and nonlinear devices.

Figure 1: SHG enhancement for 4 different MIM nanocavities with varying nanowire width.

References

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Gap-SPPs of Closely Coupled Nanowire Dimers Visualized by SERS Imaging

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Abstract

We report the first direct visualization of gap-SPPs propagating on an AgNW dimer. A self-assembled AgNW dimer loaded with a monolayer of molecules is locally excited to launch the SPPs, and the wide-field microscopy maps of surface-enhanced Raman scattering (SERS) of the molecules are acquired. The SPP maps reveal that AgNW dimers with a few nm of gap can propagate up to ~8 µm. The images also show oscillating components with periods of 400 ~ 800 nm, arising from the mode-beating between a monopole-monopole mode and a dipole-dipole gap-mode.

1. Introduction

It has been theoretically predicted that gap-plasmons of nanowire (NW)-dimers, the ones with extreme field confinement at the NW-NW junctions, may propagate several microns along the NW-axis. Such propagating gap-plasmons, due to tight field confinement, may efficiently couple with a dipole-emitter at the gap, and can minimize crosstalk with neighboring NWs. Experimentally, however, very few studies exist that successfully realize such possibility. Here, we report on the first direct visualization of the propagation of gap-plasmons of NW-dimers. The technique we employ is the wide-field imaging of surface-enhanced Raman scattering (SERS), in which SERS of molecules placed at the gap of a NW-NW junction report the gap-field intensity profiles of propagating gap-plasmons. We find that AgNW dimers (diameters of 100-150 nm) with a gap distances of 3-5 nm allow the gap-mode propagation of several microns. The SERS profiles also reveal oscillating components, indicating the beating of two propagating gap-modes. We identify, through the close comparison with electrodynamics simulations, that these two modes are the monopole-monopole and dipole-dipole gap-modes, with the two having different parallel momenta.

2. Results

The measurements were carried out on self-assembled dimers of chemically synthesized AgNWs, which have pentagonal cross-sections and an average diameter of 151 ±12 nm. The AgNWs were coated with a monolayer of biphenyl-4-thiol (BPT) and were dispersed on a glass coverslip. For the imaging of SPPs on monomeric and dimeric AgNWs, a laser beam was focused onto a terminus of NW to launch SPPs, and the Stokes-shifted emission from each point in the NW is recorded with a wide-field microscope equipped with a CCD-camera and a spectrometer.

The SERS image (Fig. 1i–m) of an AgNW dimer reveals a pattern that can be fitted to a bi-exponential function with decay-lengths of 720 nm and 5.6 µm, which are ~10-fold and ~2 fold shorter than the propagation lengths of SPP of the monomer (Fig. 1c–g). The beating pattern, which represent the existence of two simultaneously launched SPP modes, is likewise ~4-fold reduced from that of monomer. These parameters also systematically change with the change in excitation wavelength. Based on the best comparison with electrodynamics simulation and the experiment, conclude that what we experimentally observe from AgNW dimer is the monopole-monopole mode with a propagation length of l = 0.5 ~ 2 µm and the dipole-dipole mode with a propagation length of l = 5 ~ 8 µm.

Figure 1: (a) & (b) Measurement scheme and a representative SERS spectrum. (c)-(e), (h)-(k) optical, topographic and SERS images of a AgNW monomer and a dimer. (f), (g), (l), (m) SERS line-profiles and the fit.
Modeling plasmonic hot-electron generation and their role in photocatalysis

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Abstract

Plasmonic nanoparticles interact strongly with light ranging from the UV to IR, which has motivated their usage in a wide variety of applications in photonics and nanotechnology. In particular, the study of hot electron generation in plasmonic systems has gained much attention, both because of the fundamental physical interest of their ultrafast dynamics and because we can use them in applications such as photodetection or contributing to solar energy conversion strategies in photocatalytic schemes. These hot electrons occupy high-energy states, and if they stay within the plasmonic material they will rapidly thermalize and share their kinetic energy with the rest of carriers in the particle. But their high kinetic energies can also allow these hot carriers to traverse into neighboring materials, thus increasing overall photocurrents in a device or driving chemical reactions. In this talk we will describe strategies to enhance the excitation of these high-energy carriers from a theoretical perspective, and discuss their utility in several technological applications.
Single molecule studies of metal-enhanced fluorescence and resonance energy transfer interplay in graphene-metallic hybrid nanostructure

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Abstract
In this work, we use single molecule fluorescence spectroscopy to probe nanoscale interactions in hybrid nanostructures composed of graphene and silver nanowires. The presence of metallic nanoparticles or graphene in hybrid nanostructure can induce fluorescence enhancement, fluorescence quenching or their interplay in nearby emitter, depending on nanostructure arrangement.

1. Introduction
When emitter is placed in vicinity of metallic nanostructure, such as silver nanowires (AgNWs), the Metal-Enhanced Fluorescence (MEF) process can occur. This process involves plasmonic excitations, which result in local electromagnetic field modifications, thus, in optimal conditions, can yield strong increase of emission intensity as well as the radiative rate of emitters [1]. For instance, when photoactive proteins are placed in vicinity of AgNWs, their fluorescence intensity is increased due to enhanced radiative emission rate [2]. The optical properties of emitters can also be modified with Förster Resonance Energy Transfer (FRET), a process which involves two components – acceptor and donor of energy. In the context of spectroscopic results, FRET can be distinguished by fluorescence intensity quenching and fluorescence decay time shortening of the energy donor. One of the basic requirements of this process is spectral overlap between donor emission and acceptor absorption spectra [3]. For this reason graphene, which is two-dimensional material composed of carbon atoms arranged in hexagonal lattice, can be considered as a universal energy acceptor, due to his specific absorption which is uniform and constant across whole VIS-IR spectral range and equal to 2,3% of incident radiation for each graphene layer [4, 5]. It has also been shown that morphology of graphene can be used to control the FRET process in hybrid nanostructures [6]. The optimization of hybrid nanostructure architecture can enhance the desired MEF or FRET effect or achieve interplay of both [7].

2. Materials & methods
In our study we have investigated three types of hybrid nanostructures, composed of AgNWs, graphene or both. As the emitter we used Peridinin-Chlorophyll-Protein (PCP) photosynthetic complexes, which structure and optical properties are presented in Fig.1.

Figure 1: (left) PCP monomer structure, with chlorophylls marked green, peridinins marked orange and lipid molecules marked blue, embedded in protein matrix. (right) PCP optical properties: absorption (black) and emission (red) spectra.

The single PCPs are specifically conjugated to the AgNWs and then deposited on graphene or, when nanostructure consist of graphene only, deposited directly. Measurements were performed using two fluorescence microscopes: Wide-Field microscope and advanced home-built confocal fluorescence microscope, where both steady-state and time-resolved techniques have been implemented.

3. Results & discussion
We used single-molecule fluorescence spectroscopy to probe MEF-FRET interplay and the influence therefore on the optical properties of PCP. The results of time-resolved and steady-state measurements show that upon conjugation with AgNWs, the emission of single PCP complexes increases by an order of magnitude and the fluorescence decay time is shortened. Subsequently, when conjugated AgNWs are placed on graphene, the emission intensity is quenched and the fluorescence decay time is shortened,
however in this case, the shortening of decay time is associated with the energy transfer from plasmonically enhanced PCP to graphene. The observed changes can be successfully described by the MEF-FRET interplay and therefore influence on the optical properties of nearby proteins. The implementation of metallic nanowires together with graphene shows impact of both hybrid nanostructure components on fluorescence dynamics of nearby emitters.

4. Conclusions

The results are important in the context of sensing of optically active species as they bring additional way to control optical properties of hybrid nanostructures. As the MEF-FRET interplay can also be suitable for energy conversion, our experiments render graphene as a viable component of functional, plasmonic, hybrid nanostructures.

Acknowledgements

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References

Strong Coupling in Metallo-dielectric Hybrid Metasurfaces

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Abstract

The presented work involves designing a hybrid metasurfaces by incorporating merits of two different types of resonator system (metal and dielectric) and investigating novel optical features emerging from the metasurface. The metasurface design consists of a high-index resonator array on top of thick metal film with a spacer layer. Simulation studies on the metasurface shows that a strong coupling can be achieved between the anapole mode in the disk and a surface plasmon polariton (SPP) mode at the metal-dielectric interface.

1. Introduction

Metasurfaces composed of plasmonic and dielectric subwavelength resonator structures display extraordinary effects such as beam steering, wave front control, structural coloration and radiative cooling, through diverse light-matter interactions [1]. Plasmonic resonators are efficient at localizing light in subwavelength regions, but they suffer from non-radiative ohmic losses and the losses tend to increase at resonance wavelength regions reducing the Q-factor of the system. Such losses are minimal in dielectric resonators, whereas the field confinement in these resonators is lower compared to the plasmonic counterpart [2]. Therefore, by utilizing the merits of the two resonator systems one can expand the boundaries of metamaterial functionalities. Furthermore, different coupling regimes (weak or strong) can be accessed by tuning near-field interactions between these modes that lead to exotic resonant phenomena such as Fano resonance, Kerker effect and resonant absorption [2,3,4]. Recently anapole mode in high-index dielectric disk resonators is gaining attention

Figure 1. (a) Multipole decomposition of the scattering cross-section of an isolated Si nanodisk (diameter = 310 nm and height=50 nm) shows scattering dip of the anapole mode (@680 nm). (b) 2D reflectance profile of the hybrid metasurface as a function of Si nanodisk array period and wavelength. The anti-crossing of the SPP (1,0) mode and the anapole mode indicates the strong coupling between the two modes. The inset shows a typical schematic of the hybrid resonator. (c) and (d) show cross-sectional electric field intensity profiles of spectrally separated SPP (@654 nm) and anapole (@715 nm) modes, respectively, for an array period of 460 nm. (e) The cross-sectional electric field intensity profile of hybrid SPP-anapole mode at 745 nm for an array period of 540 nm.
owing to its ability to strongly confine light inside the disk. Therefore, a strong near-field interaction between an anapole mode and a plasmonic mode can be expected when the modes are close to each other both spatially and spectrally. In this work, a study is presented that focuses on designing a novel metallo-dielectric hybrid metasurfaces and investigating its optical properties. The study shows that it is possible to achieve a strong coupling between an anapole mode and a surface plasmon polariton (SPP) mode in the designed metasurface.

2. Results and Discussion

The hybrid metasurface consists of a silicon (Si) nanodisk array placed on top of a thick aluminum (Al) film with a dielectric (SiO₂) spacer layer. Finite difference time domain (FDTD) method is used to simulate isolated Si nanodisks and the hybrid metasurface. A semi-analytical multipole decomposition method is applied to determine the modes contributing to the overall scattering cross-section of the silicon nanodisks. Using this analysis, the dimensions of the nanodisk are optimized (diameter = 310 nm and height = 50 nm) to generate anapole mode. For the optimized disk placed in free space, anapole mode occurs at 680 nm as a dip in the scattering cross-section spectra (Fig. 1a). The nanodisk array excites SPP modes at Al-SiO₂ interface through grating coupling. The grating coupling is achieved in the normal incidence when,

\[ \Lambda = \frac{\lambda_{\text{SPP}}}{\sqrt{j^2 + j^2}} \]  

(1)

where \( \Lambda \) is the period of the nanodisk array and \( \lambda_{\text{SPP}} \) is the wavelength of the excited SPP. To excite (1,0) SPP mode in the wavelength region of 600-900 nm, \( \Lambda \) is varied from 400 nm to 600 nm. When \( \Lambda \) is close to 540 nm a spectral overlap between the SPP mode and the anapole mode is achieved at ~710 nm. With a spacer layer of 150 nm, a strong coupling between the anapole and the SPP mode is observed that is evident from the anti-crossing behavior of the modes as seen in the 2D reflectance profile (Fig. 1b). Cross-sectional field intensities are presented that show a typical electric field pattern of anapole mode inside Si nanodisk and SPP near-field at Al-SiO₂ interface in two cases - uncoupled (Fig. 1c, d) and strongly coupled (Fig. 1e). By varying the thickness of the spacer layer (25 nm - 200 nm), near-field interactions between the two modes are controlled. The behavior of the interactions between the hybrid modes and their coupling energy can be understood using coupled oscillator models. Furthermore, the effect of refractive index of the spacer layer directly affects SPP excitation wavelength and the efficiency of anapole excitation. Such investigations are interesting in the context of active metasurfaces [5].

3. Conclusions

The study presents a novel design of metallo-dielectric hybrid metasurface and its optical properties. The metasurfaces consists of a Si nanodisk array placed on thick Al film with SiO₂ spacer layer. Si nanodisk dimensions are optimized to support anapole mode and SPP modes are excited at normal incidence through grating coupling. By varying the array period spectral overlap between the anapole mode and the SPP mode is achieved leading to a strong coupling between the modes. This is evident from the anti-crossing of the modes in the 2D reflectance profile. The near-field interactions between the anapole and the SPP mode can be varied by changing spacer layer thickness and thereby controlling the strength of the strong coupling. The study offers a new approach to achieve strong coupling between plasmonic-Mie modes in a hybrid metasurface.

References

Nanoscale ZnO growth via localized photothermal energy conversion in plasmonic nanoantennas

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Abstract
In this work, a new bottom-up nanofabrication method based on plasmon-assisted hydrothermal synthesis (PAHS) is demonstrated. By engineering the polarization-dependent optical and thermal properties of a gold nanogap antenna, we achieve localized growth of a few-nm-thick zinc oxide (ZnO) layer at the targeted central position of the antenna. It is numerically shown that the back-action of the material synthesis on the plasmonic resonance can be used to achieve self-limited material growth.

1. Introduction
Because there is a growing need for fabricating hybrid nanophotonic structures with complex architectures, new nanofabrication methods that enable controlling material growth on a nanoscale are highly desired. Hydrothermal synthesis reactions allow controlling the growth of various materials via the temperature distribution of the precursor solution. For instance, the hydrothermal synthesis of ZnO nanowires at the surface of a gold thin film can be triggered by a laser beam via photothermal energy conversion [1−3]. So far, laser-induced hydrothermal synthesis has been demonstrated only on a microscale but not on a nanoscale. In this work, we demonstrate that a hydrothermal synthesis reaction can be used to grow a thin ZnO layer with a nanoscale accuracy by selectively exciting the localized surface plasmon resonances (LSPR) of gold nanostructures [4,5].

2. Methods
2.1. Numerical simulations
The optical and thermal responses of plasmonic nanoantennas were calculated by finite-element method using COMSOL Multiphysics. In a first step, the spatial distribution of the electromagnetic field and the absorption power of each gold domain were obtained by simulating the optical response of the gold nanostructures under plane wave irradiation. Then, the spatial distribution of the temperature was calculated by defining for each gold domain a heat source with a heat power corresponding to the previously obtained absorption power. A uniform heat power density was assumed for each gold domain due to the difference of time scale between the heat diffusion in gold and the heat diffusion in the surrounding materials (glass and water) [6].

2.2. Experimental methods
Gold nanostructures were fabricated on a glass substrate by electron beam lithography and lift-off techniques. The precursor solution for the hydrothermal synthesis reaction was prepared by mixing equal amounts of a 75 mM zinc nitrate hexahydrate aqueous solution and a 75 mM hexamethylenetetramine aqueous solution. The precursor solution was then dropped on the plasmonic chip and sealed in a microfluidic chamber. Experiments were performed by focusing a 1064 nm CW laser on the targeted gold nanostructure using 100× oil immersion objective lens (laser spot size: 2.5 μm). The plasmonic chip was washed and dried after the experiment.

Figure 1: SEM pictures of a nanobutterfly antenna before and after the PAHS of a ZnO layer on the central gold nanobar.

3. Results and Discussion
To demonstrate the PAHS of ZnO, we designed and fabricated nanobutterfly plasmonic antennas composed of
one central nanobar and two side rhombuses (Figure 1). The polarization-dependent plasmonic response of the nanoantenna makes it possible to localize the heat production at the center of the antenna when the linear polarization of the incident light is aligned with the nanobar. On the other hand, a strong electric field enhancement is achieved in the two nanogaps when the linear polarization is set perpendicular to the nanobar. PAHS experiments were then conducted using an incident laser with a linear polarization aligned with the nanobar axis of the nanoantennas. As shown in Figure 1, the selective excitation of the plasmonic resonance of the central nanobar lead to formation of a thin ZnO layer (20 to 25 nm thick) at the surface of the nanobar. Due to the much-localized temperature increase, the two side rhombuses were left without any ZnO coating. These results were confirmed by energy dispersive X-ray spectroscopy (EDS) measurements. According to our simulation results, a large red-shift of the plasmonic resonance of the nanobar is observed as soon as a few-nanometer-thick layer is formed at the nanobar surface. Thus, the temperature of the nanobar automatically decreases due to this back-action mechanism, even when taking into account the Kapitza resistance at the gold-dielectric interfaces [5]. This effect may be used to achieve the self-limited growth of a ZnO nanolayer by PAHS using a moderate laser power.

4. Conclusions

The photothermal energy conversion efficiency of gold nanostructures can be controlled via the selective excitation of their LSPR. This enables nanoscale control of the temperature in the vicinity of gold nanoantennas. In this work, we have demonstrated that the hydrothermal synthesis of ZnO can be selectively induced at the surface of resonant plasmonic nanostructures [4,5]. We designed a nanobutterfly plasmonic antenna with optimized thermal and optical responses. A few-nanometer-thick ZnO layer was successfully grown by PAHS at the surface of the selected part of the gold antenna. Based on numerical results, we have shown that the PAHS is a self-limited material growth process when using a moderate laser power.

Acknowledgements

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References

Manipulating Plasmonic Excitonic Nanomaterials with Coherent Phonons

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Abstract

Coherent acoustic phonons can modulate electronic interactions with proximal excitonic molecular species. Gold bipyramids with systematically altered aspect ratios and corresponding localized surface plasmon resonance energies, functionalized with an excitone, J-aggregated dye molecule, produce two hybridized states that exhibit anti-crossing behavior with a Rabi splitting energy of 120 meV. Such oscillatory plasmonic-excitonic nanomaterials offer a route to manipulate and dynamically-tune the interactions of plasmonic/excitonic systems and unlock a range of potential applications.

1. Introduction

Here, we show that acoustic phonons resulting from photoexcitation transiently alter the electronic coupling between a localized surface plasmon resonance (LSPR) and a molecular electronic transition. Similar systems that take advantage of the coupling of plasmonic nanomaterials have gained significant interest and shown potential in an array of applications. In this way, we demonstrate molecular sensitivity to the vibrational mode of an inorganic solid undergoing deformation. Related behavior has been observed in modulation of spatially-extended plasmonic superlattices. We use a system of highly monodisperse gold bipyramids (AuBPs) with thiacarbocyanine dye, 2,2’-dimethyl-8-phenyl-5,6,5’,6’-dibenzothiacarbocyanine chloride (abbreviated TCC) molecules on the AuBP surface, to achieve time-dependent ensemble characterization of the phonon-induced energetic modulation. Previous reports have shown that TCC can successfully attach to gold nanostructures and couple to the particle electronically resulting in a plexcitonic system with plasmon-exciton hybridized states. We characterize the static properties of several different AuBPs, with corresponding LSPR energies, functionalized with TCC (denoted TCC-AuBPs), then analyze the ultrafast dynamics of these systems to determine the effects coherent acoustic phonons on the electronic transitions. Finally, we offer a qualitative explanation for the direction and magnitude of the observed changes in coupling. The resulting paradigm, which we describe as an oscillatory plasmonic-excitonic nanomaterial, could be used as a model system in the development of photochemistry facilitated by vibrational modes as well as provide fundamental insight into plexcitonic systems or enable new applications owing to the inherent fine-tuning of the plasmonic resonance.

Figure 1 shows the extinction spectra of the TCC J-aggregate formed on several different aspect ratio AuBP ensembles with LSPRs ranging from 670-750 nm before functionalization. The TCC-AuBP ensembles exhibit broader peaks with asymmetric Fano-type line shapes consistent with plasmon-exciton coupling. Further, the hybridized system undergoes an avoided crossing with an upper and lower resonance. This anti-crossing behavior is explicitly demonstrated in Figure 1d, which displays the spectral positions of each of the two TCC-AuBP peaks along with the LSPRs of the corresponding AuBPs and the absorption peak of TCC.
Femtosecond electronic optical excitation of a TCC-AuBP assembly such as that shown in Figure 1 results in coherent acoustic phonons similar to those that have been previously observed for the ensemble, bare AuBP particles. Here, both upper and lower branches of hybrid resonances are observed to oscillate in transient extinction spectroscopy. Motions in energy space of the split features are monitored and found to shift together.

### References


Optical injection of plasmonic Janus-nanoparticles into living cells

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Summary

Devising strategies for the delivery of functionalized nanocarriers and reagents with high spatio-temporal control and directionality into living cells is critically important for manifold applications in biotechnology and biomedicine. Here, I will present that plasmonic Janus nanoparticles or ‘nanopens’ that are composed of a gold nanoparticle attached to a dielectric alumina shaft can be optically manipulated and injected into living cells [1].

By balancing the thermophoretic and optical forces that are acting on a single nanopen in a focused laser beam, we achieve accurate control of the vertical movement of the particle along the beam axis. This concept of a ‘light-fueled nanoparticle elevator’ presents an advantage over previous approaches for optical trapping or printing of plasmonic particles. Due to this improved optical control, single Janus particles can be trapped and deposited in specific locations on the surface of living cells.

While the process of optical injection involves strong laser heating of the plasmonic side of the nanopens, the temperature of the alumina stays significantly lower. Having a ‘hot’ and a ‘cold’ part as a consequence of the Janus design allows the selective functionalization of the particles with fluorescently labelled, single stranded DNA and the spatially controlled injection of genetic material while avoiding thermal degradation.

References

Novel nonlinear chiroptical effects

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Abstract
Following our recent discovery of the Hyper Rayleigh Scattering Optical Activity (HRS OA) [1], further developments [2] and related, new nonlinear chiroptical effects are reported. The new effects enable chiroptical characterization in tiny volumes of illumination.

1. Introduction
Chirality is exhibited by any system that lacks mirror symmetry. Chiral optical (chiroptical) techniques, such as circular dichroism and optical rotation are routinely used to determine the handedness of chiral molecules and inorganic particles. However, these linear optical techniques require large volumes of illumination and correspondingly large amounts of chiral analytes.

By contrast, nonlinear chiroptical techniques typically only take place in the focal point of illumination, which constitutes an illumination volume many orders of magnitude smaller than that of commercial chiroptical spectrometers. Unfortunately, so far, nonlinear chiroptical techniques have been considered technologically complex and they have not been widely adopted.

For instance, second harmonic generation circular dichroism[3] and second harmonic generation optical rotation [4] require symmetry breaking interfaces and are therefore best suited to investigating the surfaces of solids or liquids.

Another example can be found in sum frequency generation in liquids.[5,6] Yet this technique is highly complex: it requires two non-collinear beams, with different polarization to be superimposed at the same point in space and time.

Nonlinear circular dichroism or optical rotatory dispersion [7] is measured against the background of linear effects and requires large volumes. The same is true for Polarimetric z-scan [8] where the linear optical effect is required to calibrate the nonlinear one.

Two-photon circular dichroism [9] requires real energy states and in modern setups it is highly complex.

Chiroptical effects at the fourth harmonic frequency are all highly sophisticated. They require two or three beams with different polarizations to be superimposed in time and space.[10] Moreover, they can produce several beams in output, which adds a level of experimental complexity to the detection of the chiroptical signal.[11]

2. Hyper Rayleigh scattering optical activity
Our team recently demonstrated new nonlinear chiroptical effect – hyper Rayleigh scattering optical activity.[1] This effect was demonstrated in Ag nanohelices, dispersed in a liquid environment. Initially formulate din 1979,[12] this effect had eluded scientists for 40 years. Soon after our discovery, the effect was reported in molecules [13] and in Au nanohelicoids [2]. The effect is extremely sensitive and it enabled the first chiral optical characterization of a single nanoparticle, in a completely isotropic liquid environment, that is to say, away from the complicating includes of surfaces or interfaces.[14,15] Most recently, we have observed the effect at the third harmonic frequency as well, see Figure 1. Moreover, we have measured other previously unknown forms of hyper scattering optical activity.

Figure 1: Hyper Rayleigh scattering optical activity effects at the second and third harmonic frequency.

3. Discussion
Compared to all the “generation” techniques, such as second harmonic generation, third harmonic generation,
fourth harmonic generation, sum frequency generation and difference frequency generation, our method does not require coherence between individual scatterers and is therefore simpler. Compared to other scattering techniques, our method is parametric (the initial and final energy states are the same), i.e. our method proceeds via virtual energy states. By contrast, two-photon luminescence and Raman scattering techniques require real energy states that restrict the frequencies of study and therefore the applicability of such techniques.

4. Conclusions
We have demonstrated several new nonlinear chiroptical effects. These include hyper Rayleigh scattering optical activity at the second and at the third harmonic frequency. The new effects enable the possibility to probe chirality in miniscule volumes of illumination, thereby greatly reducing the amounts of chiral nanoparticles or molecules that are needed for the characterization.

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Temporal Plasmonics of metallic nanoparticle dimers: The Fano and Rabi regimes

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Abstract

In the quest of ultrafast plasmonic circuits, the combination of achieving coherent long plasmon lifetimes and rapid control temporal schemes becomes crucial for possible nanophotonic applications [1]. As such, the basic temporal dynamics of plasmonic systems need to be understood and characterized. Here we study what are the signature temporal responses of the Fano and Rabi effects in dimers of plasmonic nanoparticles [2]. The Fano and Rabi effects are characteristic responses in systems with two coupled interacting oscillators, interaction which could lead to interesting consequences in temporal responses. In their optical spectra, the Fano system possesses the peculiar destructive interference line-shape, while the Rabi system exhibits a very characteristic splitting. We find that this difference is correlated with fundamentally different temporal dynamics as well: Fano systems show at most one temporal beat after a pulsed excitation (Figure 1, right panel), whereas Rabi-like systems have a significant number of beats (Figure 1, left panel). Remarkably, both Fano and Rabi systems show coherent time dynamics with non-trivial and characteristic relaxation behaviors, which we believe should be observable in time-resolved experiments of plasmonic nanocrystal dimers, such as ultrafast spectroscopy.

Figure 1: Temporal response in Ag-Ag and Au-Ag dimers upon optical excitation (red).

References

Surface-enhanced Absorption Principle of Thin Film Sensing in the Mid-infrared

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Abstract

We fabricated arrays of periodic nanoantennas with plasmonic resonances between 1300 cm\textsuperscript{-1} and 2300 cm\textsuperscript{-1} on a single chip and demonstrated the ability of infrared signal enhancement on specific analyte with vibrational lines close to resonances of fabricated nanoantennas.

1. Introduction

Plasmonic nanoantennas (NAs) are of great interest due to their main feature, which is excitation of collective oscillations of free electrons (localized surface plasmons) coupled to the local electromagnetic field. Arrays of these structures can enhance and control the propagation of incident radiation. Moreover, one of the main properties of plasmonic antennas is the ability to change the phase and polarization of the scattered light as a component of metasurface [1]. Many different geometries of nanoantennas array, such as V-shape [1], spirals [2] and cross-shaped [3], are being investigated as an affective plasmonic metamaterial. This fact offers the opportunities for a large number of applications in different ranges of electromagnetic radiation, such as SERS in visible range, surface-enhanced infrared absorption (SEIRA) in the infrared (IR), and THz sensing.

SEIRA spectroscopy of thin films is the relevant objective that used for identification of molecular structure. This method SEIRA substrates, consisting of NAs with plasmonic resonances in the IR, make it possible to reach much higher sensitivity due to manhãcing the frequency of the plasmonic mode and the molecular vibration. SEIRA method find use in a wide range of biological [4] and medical [5] applications.

2. Design and Fabrication

We developed several designs of NA arrays for precise thin film sensing with the wavelengths of aromatic C=C bending, C–O strong stretching, and different aromatic amines in the region of 1000-1800 cm\textsuperscript{-1}. NAs size and morphology were chosen taking into account silica as the material of substrate for achieving plasmonic resonance at the wavelength of selected vibrations. Near-field distribution for the periodical NA arrays were simulated by FEM in Comsol Multiphysics. We fabricated arrays of gold Y-, inverted Y-, and V-shaped NAs by e-beam lithography in the Crestec CABL-9000C system with 150 nm width, 700 nm arm length, and 80 nm gold thickness. This geometry was chosen according to our previous research of V-shaped structures [6] and developed based on Y-shaped NAs plasmonic resonance features [7]. Morphology of fabricated structures were investigated by atomic force microscopy (AFM) in semi-contact mode (Fig. 1C). Also fabricated array were investigates by scanning electron microscopy (SEM). SEM images of part of the fabricated Y-shaped and V-shaped NA array is shown in the Figure 1A, B.

Figure 1: Fabricated gold Nanotennas. (A) SEM image of Y-shaped NAs; (B) SEM image of V-shaped NAs; (C) AFM images inverted Y-shaped NAs
In this work we used electron-transporting aluminum complex Alq₃ as an analyte layer for SEIRA experiments (Fig. 2) [8]. The strongest of Alq₃ bands are observed in the 1300-1600 cm⁻¹ fingerprint IR-region: 1330, 1380, 1470, 1500, 1580, 1605 cm⁻¹ corresponding to the ring-stretching vibrations and C-H bending mode, which is taken into account for nanoantenna design. Series of thick film with thickness from 8 to 130 nm were thermally evaporated on fabricated plasmonic substrate (evaporation parameters: pressure of 10⁻⁵ Torr, deposition rate of 7 nm/min).

![Figure 2: Single cell of fabricated SEIRA substrate, containing gold NA and layer of analyte with the same thickness.](image)

3. Discussion

Transmission and reflection spectra of fabricated structures (Figure 3) were obtained by Fourier-spectrometer Bruker Vertex 80 with IR microscope Hyperion. Absorption coefficient was calculated by simple subtraction assuming zero scattering. Fabricated NAs interact differently depending on the orientation of the linear polarization in the region of MIR spectrum: from 1000 cm⁻¹ to 2500 cm⁻¹. Thus, fabricated chip could be used as SEIRA substrate for the study of absorption lines of certain chemical. Besides, the chip could be used for selective line sensing due to the tuning the plasmonic resonance by changing the orientation of linear polarization.

![Figure 3: Obtained transmittance spectrum of gold Y-, inverted Y-, and V-shaped NAs with parallel and perpendicular orientations of linear polarization.](image)

Homogeneity and thickness of the layer were controlled by AFM Solver Pro M, NT-MDT set up (Fig. 4B). The RMS roughness measured by AFM on the 5×5 μm² scan area is below 2 nm. Also, it was observed by AFM that heights of the bar antenna and antenna covered Alq3 layer remained the same.

![Fig. 4. (A) Alq3 chemical structure, (B) Scratch line for thickness control of Alq3 layer, (C) Y-shaped NAs covered by 130 nm Alq3 layer.](image)

Enhanced absorbance as logarithm of transmittance of Y-shaped, inverted Y-shaped, V-shaped NA array is illustrated in Figure 5 (blue line). More detailed image for Y-shaped geometry illustrated in Figure 6. FTIR spectrum of the analyte was measured by the method of attenuated total reflectance (green line). All absorption lines in the region of 1300-1550 cm⁻¹ were enhanced by Y- and inverted Y-shaped NAs. Changing in orientation of polarization tune the enhanced region to 1000-1250 cm⁻¹. Moreover, fabricated V-shaped NAs cover a region up to 2500 cm⁻¹ (purple line in Figure 6), which may be important for the SEIRA signal of lipid fingerprints.
4. Conclusions

We fabricated the SEIRA chip with different geometries of NAs covering regions of particular absorption lines, which are important for sensing both aromatic bending (~1500 cm$^{-1}$) and vibrations of the acyl chains in lipids (~2500 cm$^{-1}$). Demonstrated SEIRA signal on the fabricated chip with the specific analyte open the potential for using single SEIRA substrate for precise sensing of films up to several nanometers thick. Also, the effect of linear dichroism for fabricated plasmonic structures, more pronounced for V-shape, was demonstrated, opening the opportunities for the simple and effective way of tuning the plasmonic resonance.

5. Acknowledgements

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6. References


New trends in nanophotonics and advanced materials
In situ electron energy-loss spectroscopy for nanoscale optical devices

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Abstract

We demonstrate dynamic electromechanical control over the coupling of a gold nanodisk dimer all the way to sub-nanometer-sized gaps. By combining EELS with in situ electrical actuation, we can follow the evolution of the gap size and optical properties with unprecedented spatial and spectral resolution. We show that our electromechanical device can be used as light modulator with low power consumption and high speed.

1. Introduction

One of the most intriguing properties of surface plasmons is their ability to enhance the optical nearfield. This effect has given rise to numerous applications, including near-field optical microscopy, single molecule SERS, and bio-molecular sensors. Gap-plasmon resonances in a metallic nanoparticle dimer is a prime example of such field confinement as it employs near-field coupling of two resonant antennas to further enhance the field intensity. Capacitive charge accumulation on the neighboring particle interfaces concentrates the electric field energy into the gap between the particles. As the particle spacing is reduced, the field intensity and the resonant frequency of the gap-plasmon mode become more sensitive to gap size variation. This high sensitivity to geometry renders the metallic nanoparticle dimer a promising platform for actively tunable optical nanoantennas. To achieve maximum field concentration and tunability of the resonance frequency, the gap size should be reduced to the ultimate limit.

2. Results

Here, we demonstrate dynamic electromechanical control over the coupling of a gold nanodisk dimer, and use this to systematically study the evolution of gap-plasmon resonances all the way to sub-nanometer-sized gaps. The device is prepared on a transmission electron microscopy (TEM) membrane, which allows us to apply the electrical actuation inside the microscope. By combining EELS with in situ electrical actuation, we can follow the evolution of the gap size and optical properties with unprecedented spatial and spectral resolution. We dub this new technique in situ EELS.

Two 500-nm-wide parallel Si$_3$N$_4$ cantilevers are fabricated on a 50-nm-thick TEM membrane. Next, 50-nm-thick, 100-nm-wide gold nanodisks are fabricated at the facing end of each cantilever. We use electrostatic attraction between the two cantilevers to obtain dynamic control over the inter-particle distance in the range of 0.9-35 nm.

We directly observe the spectral crossover of the bonding and anti-bonding modes, as a result of weakened capacitive coupling by electron tunneling. Initially, the bonding mode redshifts from 1.65 to 1.60 eV as the gap size shrinks from 35 to 1.5 nm. As the gap size decreases further from 1.5 to 0.9 nm, it blueshifts from 1.60 to 1.80 eV, which indicates a clear spectral crossover. By the same token, the blue-shift of the anti-bonding mode from 2.40 to 2.45 eV is switched to the red-shift from 2.45 to 2.40 eV.

Moreover, a clear bifurcation of the bonding mode appears when the gap size is reduced below 1.5 nm. While the normal bonding mode experiences capacitive coupling reduction and shows blue-shift, an additional mode emerges and shows a drastic red-shift from 1.30 to 1.00 eV (~300 nm). Spatial mapping of the EELS signals reveals that this mode can only be excited at the side regions of the dimer, which is indicative of the CTP mode. Contrary to the peak broadening of the normal bonding and anti-bonding modes, the resonance peak of the additional mode narrows as the gap size is further decreased into the sub-nanometer regime. We note that the additional mode enables extremely sensitive tuning of the resonance frequency, which can only be obtained when the gap size is shorter than 1.5 nm. As the resonance frequency shifts significantly with minuscule gap displacement (~0.6 nm), the mode could comprise a promising route toward highly-sensitive nanophotonic devices such as pressure sensor, molecular sensor, and the efficient optical switch.

With the insight from in situ EELS, we show that our electromechanical device can be used as light modulator with low power consumption and high speed.

3. Conclusion

We have demonstrated electromechanical control over the coupling of a gold nanodisk dimer using in situ EELS, which we believe may become a critical tool for accessing the performance of future optical nanodevices.
Dynamic Control of Terahertz Polarization Based on Babinet Inversion of Anisotropic Metasurfaces with Vanadium Dioxide

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Abstract

We propose anisotropic metasurfaces, which realize dynamic polarization control by switching between two states of the structures. We have to design only one of the two states linked through Babinet’s principle, because the other state automatically satisfies the required conditions. We demonstrate a reconfigurable polarizer and a reconfigurable quarter-wave plate in terahertz regions utilizing insulator-to-metal transition of vanadium dioxide in the metasurfaces. The polarization control can be realized by switching the local conductivity of the vanadium dioxide.

1. Introduction

Manipulation of polarization is essential for engineering of electromagnetic waves from microwave to optical ranges, and polarization modulation enables us to realize various applications such as sensitive measurements and information transfer. Especially in terahertz regions, where available components are still limited, the development of polarization modulators has been desired.

In this paper, we propose a metasurface functioning as a reconfigurable linear polarizer, whose transmission and reflective axes can be switched. We also demonstrate a metasurface functioning as a reconfigurable quarter-wave plate, whose fast and slow axes can be exchanged. Each metasurface is composed of two states, which can be swapped by conductivity modulation of vanadium dioxide incorporated in the structure. These two states are related through Babinet’s principle, and the required conditions for the dynamic polarization control are satisfied by designing only one of the two states.

2. Babinet’s principle

Babinet’s principle links two scattering problems: scattering from a screen with metallic structures and scattering from its complementary structure defined as the interchange between the metallic parts and holes. Assuming the structures are anisotropic in x and y directions, the transmission coefficients for x and y polarizations, denoted as \( t_x \) and \( t_y \), are generally different. Babinet’s principle guarantees the following relations:

\[
\tilde{t}_x + \tilde{t}_y(C) = 1, \quad \tilde{t}_y + \tilde{t}_x(C) = 1,
\]

where \( \tilde{t}_i \) and \( \tilde{t}_i(C) \) (\( i = x, y \)) represent transmission coefficients for the original screen and its complementary screen, respectively [1].

Here, we introduce two types of metasurfaces composed of metallic sheets and variable resistive sheets, as shown in Figs. 1(a) and (b). Suppose \( Z \) is the impedance of the variable resistive sheet, in both cases, the structure for \( Z = 0 \) can be obtained by 90-degree rotation of the complementary structure for \( Z = \infty \), and vice versa. Consequently, the transmission coefficients \( \tilde{t}^{(\text{off})} \) and \( \tilde{t}^{(\text{on})} \) for \( Z = \infty \) (off state) and \( Z = 0 \) (on state) satisfy the following relations [2]:

\[
\tilde{t}_x^{(\text{off})} + \tilde{t}_x^{(\text{on})} = 1, \quad \tilde{t}_y^{(\text{off})} + \tilde{t}_y^{(\text{on})} = 1.
\] (1)

In this paper, the variable resistive sheets are implemented by vanadium dioxide, which shows insulator-to-metal transition. Vanadium dioxide is in insulating state around room temperature, and behaves as good conduc-

![Figure 1](image)

**Figure 1:** (a) Dipole-nested checkerboard structure. (b) Anisotropically deformed checkerboard structure. Microphotographs of (c) reconfigurable checkerboard structure. (d) reconfigurable quarter-wave plate.
or above critical temperature around 65 °C for terahertz waves. Babinet inversion for isotropic checkerboard structures was realized using vanadium dioxide [3].

3. Reconfigurable linear polarizer

A first application of Babinet inversion for anisotropic metasurfaces is a reconfigurable linear polarizer. If one of off and on states is designed to function as a linear polarizer transmitting \( x \) or \( y \) polarization, the other state also functions as a linear polarizer transmitting the orthogonal polarization, owing to the Babinet’s principle represented by Eq. (1). The fabricated metasurface shown in Fig. 1(c) is designed to satisfy \( \bar{\ell}_y^{\text{off}} = 1, \bar{\ell}_x^{\text{off}} = 0 \) and \( \bar{\ell}_y^{\text{on}} = 0, \bar{\ell}_x^{\text{on}} = 1 \) around 0.81 THz. In experiments in terahertz regions, we demonstrate that the metasurface transmits \( y \) polarization at 300 K and \( x \) polarization at 370 K.

4. Reconfigurable quarter-wave plate

A second example is a reconfigurable quarter-wave plate. In a single-layer metasurface without loss, the transmission coefficients of the quarter-wave plate should be \( t_x = (1 \pm j)/2 = e^{\pm j\pi/4}/\sqrt{2} \) and \( t_y = (1 \mp j)/2 = e^{\mp j\pi/4}/\sqrt{2} \). From Eq. (1), the 90-degree-rotated complementary structure for the anisotropic metasurface designed as a quarter-wave plate functions as a quarter-wave plate whose fast and slow axes are exchanged [4]. Figure 1(d) shows the microphotograph of the fabricated metasurface [5], which is designed to satisfy the following relations: \( \bar{\ell}_x^{\text{off}} = (1+j)/2, \bar{\ell}_y^{\text{off}} = (1-j)/2 \) and \( \bar{\ell}_y^{\text{on}} = (1-j)/2, \bar{\ell}_x^{\text{on}} = (1+j)/2 \). The metasurface is equipped with two electrodes, which are used to inject electric current to induce Joule heat in the vanadium dioxide. From the transmission spectra for \( x \) and \( y \) polarizations, we estimate normalized Stokes parameters for the incidence of 45-degree linear polarization using the following definition \( S_3/S_0 = 2 \text{Im}(\bar{\ell}_y^2)/(|\bar{\ell}_x|^2 + |\bar{\ell}_y|^2) \). If the output wave is perfect circularly polarized light, \( S_3/S_0 \) becomes \( \pm 1 \), whose sign determines the helicity of the waves. Figure 2 shows derived Stokes parameters for the currents of 0 mA (no current) and 180 mA. It is confirmed that the helicity of the output terahertz is reversed around 0.68 THz owing to the phase transition induced by injected currents.

5. Conclusions

We have proposed two applications of anisotropic Babinet-invertible metasurfaces: the reconfigurable polarizer and quarter-wave plate. In both cases, we have to design only one of the two states, because the other state automatically satisfies the required conditions thanks to Babinet’s principle. We have demonstrated dynamic switching of the linear polarizer and quarter-wave plate in the terahertz regions. The polarization control is realized not by physically rotating the whole structures but by switching the local conductivity of vanadium dioxide via the control of the temperature or electric currents.

Acknowledgement

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References


The Wonderful World of Flat Bands

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Abstract

Certain lattice wave systems in translationally invariant settings have one or more spectral bands that are strictly flat or independent of momentum in the tight binding approximation, arising from either internal symmetries or fine-tuned coupling [1]. These flat bands display remarkable strongly interacting phases of matter. Originally considered as a theoretical convenience useful for obtaining exact analytical solutions of ferromagnetism, flat bands have now been observed in a variety of settings, ranging from electronic systems to ultracold atomic gases and photonic devices [1],[2]. I will review the design and implementation of flat bands and chart future directions of this exciting field.

Plasmochromic dynamic color modulation

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Abstract

Plasmonic-electrochromic (“plasmochromic”) devices have recently gained significant interest in the research community, due to the dynamic optical properties of the electrochromic material and the high sensitivity of the plasmon to its dielectric environment. Here, plasmochromic resonance modulation is used to create a dynamic reflective display with a wavelength modulation of over 64 nm in the visible range. The results are verified via FDTD analysis, which projects a maximum wavelength shift of over 100 nm.

1. Introduction

Plasmonic phenomena have significantly advanced the field of integrated optics and photonics. With their inherent ability to localize electrical fields to a fraction of the original extent, plasmons can be employed to substantially increase the light-matter interaction.\textsuperscript{1} Recently, plasmonic metal-insulator-nanohole (MIN) structures have shown great promise as structural color printing devices,\textsuperscript{2} with the shortcoming of the static nature of the color generation. Thus, a controllable environment for the plasmonic structure is necessary to create full color switching and modulation. Electrochromic oxides, such as WO\textsubscript{3}, NiO\textsubscript{2}, or V\textsubscript{2}O\textsubscript{5}, change their optical properties upon oxidation or reduction, promising full control over the surface plasmon resonance. The electrochromic process in WO\textsubscript{3} alters the refractive index from $n = 2.1$ to $n = 1.7$ while inducing dielectric loss. Through electrochromic plasmon modulation, color tunable devices based on colloidal gold nanoparticles,\textsuperscript{3} and sub-wavelength gold nanoantennas have been realized.\textsuperscript{4} Here, we employ a scalable polystyrene nanosphere lithography process, to create a high chromaticity, wide range color modulation (64 nm) nanocavity device with high electrochemical lifetime (>100 cycles) and low power consumption.\textsuperscript{5}

2. Experimental Section

2.1. Polystyrene Nanosphere Lithography

Polystyrene nanospheres were synthesized and employed as a colloidal mask for the nanohole array. The synthesis briefly followed procedures published elsewhere.\textsuperscript{7} The resulting nanospheres show high mono-dispersion at a diameter of 224 nm.

2.2. Device fabrication

The prototype plasmochromic nanocavity consists of a thick gold mirror (100 nm) sputtered onto borofloat glass, followed by a 120 nm WO\textsubscript{3} film and subsequently the 20 nm thick gold nanohole array. For device integration, a glass/ITO counter electrode was assembled using double sided silicon tape as a sealant. The space in between the electrodes is filled with 1M LiClO\textsubscript{4} in propylene carbonate as the electrolyte.

3. Discussion

The plasmochromic nanocavity device introduced here shows a high color modulation range of over 64 nm. Figure 2 shows the results obtained by spectro-electrochemical measurements performed on an assembled nanocavity device. As seen in Fig. 2(a), the lithiation process leads to an enormous change in reflected wavelength, resulting in reflected colors ranging from deep red in the delithiated state (0 mC/cm\textsuperscript{2}) over orange, (1.5 and 3 mC/cm\textsuperscript{2}) and yellow (4 and 6 mC/cm\textsuperscript{2}) to green (8 mC/cm\textsuperscript{2}). The spectra for the obtained color images are shown in Fig. 2(b). The peak intensity decreases to approximately 30% during the lithiation process, owing to the introduced extinction. Nonetheless, a peak shift of over 64 nm is observable.
Fig. 2(c) shows simulation results using the same light source and experimentally obtained refractive index data for the electrochromic oxide. We can further predict, that with the right choice of light source, theoretical wavelength modulation of over 100 nm is possible.

The introduced device shows a high electrochemical lifetime of 91% capacity retention after 100 sweeping cycles. Furthermore, the bi-stable nature of the electrochromic process leads to low energy consumption, with over 90% charge retention in a switching cycle. By comparing, FDTD simulations with the obtained results, we can predict higher achievable modulations and analyze shortcomings of the presented device.

4. Conclusion

Via a scalable fabrication process, we created a plasmochromic nanocavity device, able to create highly chromatic reflectance colors. The introduced device geometry allows 64 nm of wavelength shift modulation at low power consumption. We further show, that FDTD simulations are suitable to design plasmochromic nanocavity devices, by comparing experimental results with simulation data.

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References

Plasmonic nanolasers modulated by current on graphene-insulator-metal structures

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Abstract

We propose a plasmonic nanolaser on graphene-insulator-metal structures and experimentally demonstrate the current modulated lasing behavior. Graphene serves as a two-dimensional material with high electron mobility, which is beneficial to external current injection. When the current is applied, it is obvious to observe the peak intensity dissipation and blue-shifted of the lasing signal. This work exhibits the great potential in active plasmonic devices.

1. Introduction

The development of optics is inevitably progressed to nanoscale in technology improvement. Surface plasmon polariton (SPP) formed by the coupling between surface plasmons and photons serves as a potential candidate for breaking the optical diffraction limit and squeezing the optical field into the nanometer regime. Consequently, many SPP-based designs, such as plasmonic lenses, antennas, and resonators [1], successfully operate in the sub-wavelength scale and exhibit extraordinary performance. The plasmonic nanolaser with an ultra-compact mode volume shows the ability to improve the Purcell effect and achieve the thresholdless lasing [2]. However, some operation conditions, including the ohmic loss in metal, surface roughness, and thermal accumulation, become significant when the structural size goes to a very small one. Notably, inserting monolayer graphene into the laser cavity has already been proved to provide many benefits, such as reducing the internal loss of SPP mode [3], effectively easing the surface scattering, and helping for the heat dissipation [4]. It’s also well known the electron mobility in graphene is very high [5], which is easy to achieve external current injection, and further shows the potential in current modulation.

In this study, the proposed plasmonic nanolaser is shown in Figure 1, different from common semiconductor-insulator-metal (SIM) nanolaser, which includes a ZnO nanowire, an Al₂O₃ separation layer, and an aluminum template, the graphene layer is inserted between the ZnO nanowire and Al₂O₃ separation layer to construct a graphene-insulator-metal (GIM) platform. On the GIM template, the electrode pad is made to apply external current. By controlling the current passing through the graphene, we would be able to demonstrate current modulated lasing behavior on GIM plasmonic nanolaser at UV wavelength.

2. Structure and Fabrication

Molecular beam epitaxy (MBE) was applied to grow the single crystalline Al film. Subsequently, we used photoresist on the sample to pattern the desired structure and then deposited the SiO₂ and Al₂O₃ layer by plasma enhanced chemical vapor deposition (PECVD) and atomic layer deposition (ALD). Afterward, a lift-off process was executed, and then graphene was transferred on metal templates. Finally, we deposited the electrodes on top of graphene by e-gun.

Figure 1 (a) The schematic diagram of the plasmonic nanolaser on GIM structures with metal electrodes. (b) The electrodes are wire bonded to the Printed Circuit Board (PCB) pads and connected to a current source.
threshold and blue SPP mode, leading to an extra ad nonreciprocal effect breaks the propagation symmetry of the blue shifts the function of applying current from 0 mA to 200 mA, and then reversely behavior on GIM structure Furthermore, to realize the lasing behavior of the plasmonic nanolaser on GIM structures, the photoluminescence spectra at different pumping power was measured at 77K, as shown in Figure 2a. A dramatic intensity increase can be experimentally measured when the pumping power is above the lasing threshold, which is around 77 μW, and a striking lasing peak can be observed at 122 μW. The low lasing threshold of the plasmonic nanolaser on GIM structures is due to the increasing plasmon frequency of Al, which is induced by the work function difference between the graphene and Al. Furthermore, to demonstrate current modulated lasing behavior on GIM structures, we tuned the applying current from 0 mA to 200 mA, and then reversely turned back to 0 mA, the measured peak intensity and peak wavelength as the function of applying current are shown in Figure 2b. As the applying current increases, the measured peak intensity gradually decays and the peak wavelength simultaneously blue shifts. This is because of the current induced nonreciprocal effect breaks the propagation symmetry of the SPP mode, leading to an extra addition of the lasing threshold and blue-shifted [6].

3. Results and Discussion

First of all, we used a 355 nm third-harmonic generation Nd:YVO₄ pulsed laser with a 1 kHz repetition rate and a 0.5 ns pulse width as the optical pumping source in the μ-PL system. Subsequently, the sample was loaded in the vacuumed chamber with pressure below 10⁻⁶ bar, and the temperature of the chamber can be tuned from 77 to 300 K. To realize the lasing behavior of the plasmonic nanolaser on GIM structures, the photoluminescence spectra at different pumping power was measured at 77K, as shown in Figure 2a. A dramatic intensity increase can be experimentally measured when the pumping power is above the lasing threshold, which is around 77 μW, and a striking lasing peak can be observed at 122 μW. The low lasing threshold of the plasmonic nanolaser on GIM structures is due to the increasing plasmon frequency of Al, which is induced by the work function difference between the graphene and Al [3].

4. Conclusions

The plasmonic nanolaser on GIM structures was successfully fabricated, and not only exhibited the outstanding lasing performance but also demonstrated the current modulated lasing behavior. Before applying an external current, the lasing threshold is as low as 77 μW, and the obvious lasing signal can be experimentally measured above the lasing threshold. After applying an external current, the peak intensity decays and the peak wavelength blue shifts. Consequently, a dynamic modulation method of plasmonic nanolaser on GIM structures is achieved by external current injection. It could be predicted that GIM structures will become an important building block in active plasmonic devices.

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References

Bloch surface wave platform in the near- and mid-infrared regions

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Abstract

Bloch surface wave (BSW) platform opens up new possibilities in the design of sensors and components for photonic circuits owing to its superior properties such as low propagation losses that enable long optical communication length and large surface sensing area. Here, we report a BSW platform realizing well-coupled BSW in a wide spectral range from the NIR to the MIR with possible applications in light guiding and sensing.

1. Introduction

Bloch surface waves (BSWs) can be excited at the interface between a one-dimensional photonic crystal and a dielectric medium. In contrast to the widely studied surface plasmon polaritons, BSWs do not require any metals that produce ohmic losses and nanostructures that require nanopatterning. Taking advantage of the readily available thin film technology, BSWs can be produced with superior properties including long propagation length, wide resonance wavelength range, and high-quality (narrowband) resonance. Therefore, BSW is being considered as an alternative to surface plasmon polaritons in several applications such as sensors and optical components. However, the reported BSW platforms still require a large number of alternating layers to sustain BSWs and have not been demonstrated in the important mid-infrared region. Finding a means to decrease the number of the multilayers and to extend the BSW wavelengths to the useful mid-infrared region is therefore highly desired.

2. Results and Discussion

Here, we report a Ge/SiO$_2$ multilayer that can sustain BSWs in a wide wavelength range. In contrast to the reported BSW platform consisting of Si$_3$N$_4$/SiO$_2$ multilayer and requiring more than six pairs to excite BSWs, the BSW modes with the proposed Ge/SiO$_2$ multilayer are obtained with only two pairs. The dispersion diagram of the proposed system is shown in Figure 1 and the comparison between the electric field profile along the multilayer cross-sections are shown in Figure 2. Under the condition of TE-polarized incident light, the simulated electric field distribution reveals an evanescent decay of the field at the interface between the multilayer and air. The maximum of the electric field corresponds to the top of the multilayer structure (i.e., interface between the top layer and air). As a result of the properties of the proposed multilayer system, the required total thickness for exciting the same BSW mode using the Ge/SiO$_2$ multilayer was reduced by approximately two times and BSW modes could be experimentally demonstrated in the MIR region. Finally, the observed BSW propagation length is of the order of mm which is much longer than the propagation length for the six-pair Si$_3$N$_4$/SiO$_2$ multilayer (of the order of a few micrometers). Design of the NIR and MIR modes will be discussed as well as the possibility to guide the surface wave on the presented platform.

Figure 1: The dispersion diagram of the Ge/SiO$_2$ BSW multilayer.
3. Conclusions

The presented Ge/SiO$_2$ BSW multilayer can be employed in a wide range of applications due to its superior properties in terms of available wavelength range (up to MIR) and propagation length (mm). We envision the use of the presented BSW multilayer to realize MIR spectroscopy for the identification of biomaterials and optical circuits with ultra-long propagation length.

Acknowledgements

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References


Strong light-matter coupling: new trends in plexitonics

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Abstract

We report our recent results of research of plasmon-exciton interactions in Au and Au@Ag nanorods integrated with J-aggregates of cyanine dyes is presented. In all developed hybrid nanostructures, the anti-crossing behavior of the hybridized modes can be tracked using a number of spectroscopic techniques such as absorption, photoluminescence (PL) and magnetic circular dichroism (MCD).

1. Introduction

The effect of a strong exciton-plasmon coupling, which, in general terms, is associated with the resonance interaction between a quantum emitter and a confined electromagnetic field is being intensively studied both for a deeper understanding of the fundamental quantum-electrodymanical aspects of this phenomenon and for the development of many applications.[1] Three different sets of results will be reported, obtained, using PL and MCD spectroscopies. Firstly, while the observation of Rabi splitting in extinction or transmission spectra of plexitonic structures that combine metal nanorods (NRs) and J-aggregates has been reported in a number of publications PL properties of a plexitonic hybrid system in the strong coupling regime are more elusive to experimental investigation.[2] Secondly, although methods based on magneto-optical (MO) activity measurements, such as MCD spectroscopy and magneto-optic Kerr effect, take an important place in the battery of tools for materials characterization, until very recently, these methods have not been used to study plexitonic structures in a strong coupling regime. [3] Finally, apart from “classical” double-component strongly coupled systems, another direction with significant untapped potential in the field of light–matter interactions is the study of strongly coupled multicomponent systems. The emergence of multiple Rabi splitting in such systems is of considerable interest and relevance for both fundamental and applied science, providing remarkable opportunities for studies of multimode hybridization and energy transfer.[4]

2. Results and discussion

2.1. Rabi splitting in PL spectra of hybrid structures

Recently we thoroughly investigated the interactions between localized plasmons in gold NRs and excitons in J-aggregates of a cyanine dye under ambient conditions. Thanks to our sample preparation procedure we are able to track a clear anticrossing behavior of the hybridized modes not only in the extinction but also in the PL spectra of this hybrid system. Notably, while previous studies often found the PL signal to be dominated by a single mode (emission from so-called lower polariton branch), we followed the evolution of the two PL peaks as the plasmon energy was detuned from the excitonic resonance.

Figure 1: Extinction and PL spectra of hybrid J-aggregates/gold NRs complexes, and spectrum of pure J-aggregates.

Both the extinction and PL results are in good agreement with the theoretical predictions obtained for a model that assumes two interacting modes with a ratio between the coupling strength and the plasmonic losses close to 0.4, indicative of the strong coupling regime with a significant Rabi splitting estimated to be ∼250 meV.
2.2. Magneto-optical activity

We also demonstrated that plasmonic nanostructures may strongly enhance the magneto-optical activity of nonmagnetic organic compounds linked to their surfaces, allowing for their MO detection at room temperature and weak magnetic fields (<1 T) (Fig. 2).

![Absorption spectra and MO activity enhancement](image)

We further showed that the MO activity enhancement strongly depends on the detuning between the localized plasmon resonance of the nanostructure and the characteristic excitation in the organic compound, yielding the MO activity of the latter at zero detuning as strong as that of the plasmon. This means that the MO activity could be utilized for the fundamental investigation of properties of hybrid organic/inorganic systems in the strong coupling regime.

2.3. Multiple Rabi splittings in a strongly coupled plasmonic system

We have shown that strong coupling between a plasmon and two excitons of J-aggregates of different dyes in multilayer nanostructures can lead to double Rabi splitting, significantly expanding the region of energy splitting between the states of plexcitons.

![Absorption spectra of J-aggregates](image)

Figure 3: (a) Absorption spectra of the hybrid structure of J-aggregates of TCI dye and Au@Ag nanorods (blue), and hybrid system of J-aggregates of TCI and Au@Ag NRs (green), and the hybrid structure of J-aggregates of two fluorophores (TCI and DBI) and Au@Ag nanorods. Inset shows TEM image of core–shell Au@Ag nanorods with average aspect ratio 2.5. (b) Absorption spectra of bare core–shell Au@Ag NRs (black) and absorption spectra of J-aggregates of TCI (blue) and DBI (red) fluorophores.

All obtained experimental results, supported by theoretical modeling, convincingly demonstrate a remarkably strong interaction of J-aggregates of two dyes and the plasmon system in the developed structures. Exciton–plasmon strong coupling in a complex system consisting of two layers of J-aggregates of different dyes on Au@Ag NRs’ surface is confirmed not only by theoretical modeling but also by the results of MO activity in the same hybrid structures, which is the ultimate verification of the strong coupling in the system for each type of excitons.

3. Conclusions

Formation of coupled hybrid systems, where specific molecules are coupled to plasmonic nanostructures and acquire magnetic properties, paves the way toward the development of novel magnetic methods for sensing, which are intrinsically insensitive to the (organics) scattering background and thus offer a significant advantage over conventional spectroscopy techniques. The development of a multicomponent system with extended Rabi splitting represents a new paradigm for various applications and opens up ample opportunities for research of multimode hybridization and fast and effective energy transfer between two excitons strongly coupled to plasmonic nanostructures.

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References


Plasmonics aerosols to govern light

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Abstract
We show the experimental demonstration of a plasmonic aerosol and discuss the significance of uniting the fields of plasmonics and aerosols.[1] We find that the aerosols are optically homogeneous, thermodynamically stable, with wide wavelength tunability, and extremely large sensitivities to their environment. Plasmonic aerosols may therefore provide a novel medium to govern light-matter interactions, thereby opening up innovative opportunities.

1. Introduction
Plasmonic materials have revolutionized our ability to control the flow of light through materials. By resonantly coupling light onto the surface of plasmonic nanoparticles the ability to optically sense and signal at nanometer length scales has been realized, leading to unique materials. However, for all the exciting opportunities to-date, these plasmonic materials are typically constrained to only a few phases of matter, either as 2D surfaces or dilute liquids, thereby limiting their full possibilities. We recently suspended gold nanorods in air and simultaneously measured the optical spectra, demonstrating an optically homogeneous and thermodynamically stable plasmonic aerosol. Furthermore, elucidating the fundamental spatio-temporal properties of the aerosols may potentially lead to applications in climatology, astronomy, petroleum, vacuum microelectronics, nonlinear optics, nanojet printing, molecular diagnostics and nanomedicine fields.

2. Discussion
To efficiently aerosolize the nanorods and measure their properties in situ at benchtop scales, we developed the Nanoparticle aeRosol (NRL) instrument (Fig 2a). An aqueous suspension of gold nanorods was transitioned from the liquid to the gas state using a Venturi tube to flow high velocity air over a liquid reservoir of nanorods, pulling the suspension into the airstream. The airstream is driven into a vertical plate (not shown in Fig 2a). Most of the suspension is condensed onto the plate and recycled back into the reservoir. However, upon striking the plate, very small water-nanorods droplets are formed, ~300 nm diameter. The concentration of nanorods was set to be equal to one nanorod per droplet or less.

The absorbance spectra of gold nanorods with aspect ratios of 5, 15 and 30 in the gas phase are shown in Fig. 2b. The corresponding longitudinal absorbance peak ranged from visible to infrared wavelengths. The relatively large Q-factor implies the nanorods are uniformly dispersed. The magnitude of the absorbance peak remained constant in time providing evidence the nanorods are thermodynamically stable. The constant peak magnitude also implies the aerosols are optically homogeneous, which is expected, since the nanorods are smaller than the wavelength of light. The density of nanorods in the Herriott cell was ~10^{11} NR/m³.

We show the shift in the longitudinal absorbance peak wavelength as the host refractive index is varied, can be approximated if the longitudinal depolarization factor (L₉) and plasma wavelength (λ₉) of the gold nanorods are known (model, Fig. 2c). The model relationship was confirmed by comparing to simulation and experimental results (Fig 2c).
3. Conclusions

In summary, the demonstration of plasmonic aerosols may enable new opportunities to govern light-matter interaction in the gas phase. The aerosols are homogeneous, stable, tunable and sensitive to their environment making them promising candidates to sense and signal from nano- to macro-scales.

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References

Metasurface enabled ultrafast polarization and on-chip light shaping

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Abstract

We demonstrate the versatility of dielectric metasurfaces to (i) shape the temporal evolution of ultrafast optical pulses, and (ii) discuss their applications towards creating integrated photonic interfaces with quantum systems.

1. Introduction

Over the last decade, flat optical elements composed of an array of deep-subwavelength dielectric or metallic nanostructures of nanoscale thicknesses – referred to as metasurfaces – have revolutionized the field of optics and nanophotonics [1-2]. Because of their ability to impart an arbitrary phase, polarization or amplitude modulation to an optical wavefront as well as perform multiple optical transformations simultaneously on the incoming light, they promise to replace the traditional bulk optics in applications requiring compactness, integration and/or multiplexing. In this talk, we demonstrate the versatility of spatial shaping metasurfaces for applications such as high numerical aperture focusing or generation of novel polarization states of light as well as holograms operating from the deep-ultraviolet to the terahertz frequency range. We further discuss the fabrication and material constraints for their applications as flat, ultrathin optical elements across the entire electromagnetic spectrum. Finally, we demonstrate direct integration of metasurfaces on integrated nanophotonic chips for their applications as a compact and efficient interface to quantum systems. Through spatial multiplexing of metasurfaces integrated with grating out-couplers directly on a nanophotonic chip, we show the ability to create arbitrary optical fields in the far-field to enable applications such as cold atom traps and atomic clocks. We conclude by discussing the ability of metasurfaces to fully shape the spatio-temporal properties of light at the ultrafast time scale, and on nanometer length scales.

2. Metasurface enabled spatio-temporal beam shaping

2.1. Ultrafast polarization shaping

We demonstrate the ability of metasurfaces to arbitrarily shape the temporal evolution of ultrafast optical pulses. This requires independent control over the amplitude, phase and/or polarization of the spectral lines covering the entire bandwidth of an optical pulse. We achieve this by designing a metasurface to operate on the spectral components of an ultrafast pulse that are separated spatially using a Fourier transform setup [3]. By designing the nanopillars constituting the metasurface to act as nanoscale phaseshifter, quarter-wave or half-wave plates, we achieve arbitrary control over the desired pulse shape over a spectral bandwidth of > 100 THz with a spectral resolution of ~ 100 GHz, only limited by the size of our optics.

The pulse shaper is based on a Fourier-transform geometry where the metasurface is positioned in the focal plane. Rectangular silicon nanopillars of the metasurface are fabricated on a fused-silica substrate, with dimensions carefully designed to provide the targeted spectral phase for two orthogonal polarizations. To demonstrate the flexibility of this approach, we implement a polarization twisting function, in other words gradually rotating a linearly polarized input light within the pulse duration, with a user-specified rotation speed (Fig. 1). We discuss the advantages of the metasurface approach to pulse shaping over the more traditional use of spatial light modulators to do the same. Finally, ongoing work on extending the spectral resolution of the system to sub GHz range enabling control of individual frequency comb lines from an ultrafast oscillator for applications in optical arbitrary waveform generation will be presented.

Figure 2: Metasurface enabled polarization shaping of ultrafast pulses. The linear polarization rotates $2\pi$ within the pulse duration.
2.2. Metasurface enabled integrated photonic interfaces to quantum systems

In the second part of the talk, we will demonstrate the versatility of spatial shaping metasurfaces to be directly integrated on integrated photonic chips for their applications as an interface to quantum or biological systems (Fig. 2). Through spatial multiplexing of metasurfaces integrated with grating out-couplers directly on a nanophotonic chip, we show the ability to create arbitrary optical fields in the far-field that may enable applications such as optical trapping, biosensing or LIDAR. The approach relies on using nanophotonic waveguides to guide light within the chip (shown here for a Si$_3$N$_4$ ridge waveguide on SiO$_2$) and expanding the beam on chip using a slab mode converter. The beam is outcoupled using apodized grating to achieve free space Gaussian beams of diameter ~ 250 µm. By fabricating metasurfaces on top of the grating out-couplers, we demonstrate the ability to simultaneously and independently change the directionality, divergence and polarization of the outgoing beam with arbitrary control. Hence the device is able to deliver shaped light off-chip with high precision in an ultra-compact platform without the need to for any free-space bulk-optics. We discuss ongoing work to utilize this platform to create chip scale atomic clocks.

Figure 2: Metasurface-integrated photonic platform to create arbitrary spatial field off an integrated nanophotonic chip.

3. Conclusions

In conclusion, we show the versatility of dielectric metasurfaces as replacement for traditional spatial light modulators both for temporal and spatial domain shaping of optical fields. The ability to directly integrate them, monolithically in a CMOS platform, with photonic chips will enable novel applications in the areas of biosensing and quantum optics.

Acknowledgements

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References

Low-Loss On-Chip Surface Grating Couplers Engineered Using Subwavelength-Structured Metamaterials

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Abstract
The presence of low-loss optical interfaces is arguably one of the key factors to succeed for silicon photonics. Here, we report on our latest advances in subwavelength-structured and metamaterial-engineered fiber-chip grating couplers with a \( L \)-shaped waveguide profiles. Grating couplers are made in silicon-on-insulator platform and facilitate robust sub-decibel coupling of light with device features lying well in the range of available fabrication technologies.

1. Introduction
Silicon (Si) photonics is recognized as a scalable integration technology to deploy complex optical circuits in many applications. Si photonics technology exploits high-volume manufacturing of the microelectronics industry, and thus offers attractive and low-cost solutions for integrated circuits. Surfing areas such as optical communications, interconnects, and sensing, among others, undoubtedly present a good opportunity for photonics to forward the development from research laboratories to industry [1]. However, the low-loss interconnection between Si chips and optical fibers poses a challenge for many years to the successful demonstration of these applications. The problem of light coupling in and out of the chip has turned Si photonics into a field with a long history of research [2,3].

Fiber-optic chip interfaces with diffraction gratings are, indeed, a widely adapted solution to overcome the mode size disparity between sub-micron Si waveguides and standard single-mode optical fibers (SMF-28) and in turn allowing a low-loss coupling [2]. Despite the penalties in loss, polarization, and bandwidth compared to the edge couplers, grating couplers have better tolerance to fiber attachment and enable relaxed positioning on the chip with fast wafer-scale probing. All these features facilitate the integration and packaging as well as favoring process automation and mass-scale production [3].

In the course of years, variety of surface grating couplers were designed, fabricated, and tested, giving a fiber-chip coupling loss below -1 dB [4-13]. Achieving this goal is, indeed, still quite challenging. The state-of-the-art methods for sub-decibel (sub-dB) devices are rather complex and/or more expensive to be produced in Si-foundries on a large-scale. This includes grating couplers with metal/Bragg mirrors underneath [4,5], overlayers [6], customized Si substrates or processes [7], and multi-level concepts [8].

In this invited talk, we present our recent progress in development of low-loss metamaterial-engineered surface grating couplers. Particularly, we focus on a versatile \( L \)-shaped waveguides made in silicon-on-insulator (SOI) technology, with ability to favor robust sub-dB coupling of light and device layouts that are compatible with fabrication techniques available in open-access Si photonics foundries.

![Figure 1: Uniform L-shaped grating coupler implemented on SOI with 310-nm Si layer and 720-nm oxide. (a) Side view schematic. Coupling loss versus wavelength: (b) simulation and (c) experiment. (d) Scanning electron microscopy image of a fabricated uniform grating coupler.](image-url)

2. \( L \)-shaped fiber-chip grating couplers
We elaborate on fiber-chip grating couplers implemented on SOI platform, with 310-nm Si layer and 720-nm oxide. \( L \)-shaped couplers, shown in Fig. 1a, are formed by using two lithography and etching steps. Such a grating coupler benefits from a two-level waveguide profile as an effectively blazed structure that facilitates superior radiation performance. The grating diffraction, in particular, is controlled through asymmetric scatterers in deep and partial etch grating trenches, yielding constructive and destructive
interference in the up and down direction. This may provide a grating directionality close to 100% for a wide range of device dimensions compatible with available fabrication tools [9]. Uniform coupler design predicts a coupling loss of -2.1 dB, as shown in Fig. 1b. Performance of uniform designs are largely limited by back-reflections at the waveguide-grating junction and the exponential-decaying profile of diffracted grating beam.

L-shaped couplers were fabricated on 300 mm SOI’s in a CMOS foundry line thanks to 193-nm deep-ultraviolet optical lithography. Scanning electron microscopy image of fabricated device is shown in Fig. 1d. Figure 1c shows a peak coupling loss of -3.4 dB measured at a wavelength of 1560 nm. Spectral response exhibits a distinctive Fabry-Perot fringes with magnitude of ~0.85 dB. This corresponds to a grating reflectivity of about 8% [9].

It is worth mentioning that grating couplers with an L-shaped waveguide profile constitute a quite versatile and scalable design approach. To be more specific, in recent years, L-shaped grating couplers have attracted a lot of attention from the community. L-shaped structures were optimized for a vertical coupling in single [10] and in two polarization states [11], or were implemented on other photonic platforms to assist low-loss optical coupling between chips and fibers [12,13].

Figure 2: Apodized L-shaped grating coupler engineered thanks to a subwavelength-structured metamaterials. (a) Side view schematic. Simulations: (b) coupling loss versus minimum feature size of the subwavelength grating and different number of apodized periods. (c) Coupling loss versus wavelength for grating coupler design with 5 apodized period and different critical dimensions. (d) Scanning electron microscopy image of fabricated apodized grating coupler with 5 subwavelength-engineered periods. Inset: Close-up view of the subwavelength grating structure at the waveguide-grating junction.

Figure 2a shows a side view of a L-shaped grating coupler engineered with subwavelength-structured metamaterials. By using metamaterials within the etched grating trenches, the coupling strength is easily controlled and the outstanding radiation performance remains almost unaffected [14]. Figure 2b shows simulated coupling loss of metamaterial-assisted L-shaped couplers as a function of the minimum feature size of the transversal subwavelength structure and this for designs with 3 and 5 apodized periods. According to simulations, exceptionally low fiber-chip coupling is predicted for a wide range of critical dimensions. The peak coupling loss of -0.5 dB is calculated for device design with 5 metamaterial-engineered periods. Moreover, a rather low penalty for coupling loss of only ~0.4 dB is found for a wide span of critical dimensions in a 50 nm to 200 nm range. This way, device layouts are well compatible with fabrication technologies presently accessible in Si-foundries, including both sub-100-nm pattern high-end immersion and conventional deep-ultraviolet optical lithographies [1]. Figure 2c shows simulated coupling loss as a function of the wavelength for L-shaped coupler design with 5 apodized periods and this for different minimum feature sizes of the subwavelength grating. In all cases, the coupling loss is well below a 1-dB threshold in a wavelength range typically larger than 25 nm.

3. Conclusions

We demonstrated our recent results on low-loss metamaterial-engineered surface grating couplers based on versatile L-shaped waveguides. Such devices showed the ability to promote robust coupling of light with losses potentially below 1 dB and feasible layouts compatible with fabrication techniques used in Si photonics foundries.

Acknowledgements

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References

Few-femtosecond plasmon transients probed with nm-scale sensitivity

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Abstract

Photoelectron probing of few-femtosecond plasmon transients on nanostructures reveals the ultrafast dynamics of localized plasmon oscillation decay with nm-scale sensitivity at plasmonic hot spots.

1. Introduction

Full spatiotemporal resolution of the evolution of plasmonic fields is a major goal in plasmonics in order to investigate the buildup and decay of collective electron phenomena. Here, we demonstrate few-femtosecond probing of plasmon transients uniquely combined with nm-scale sensitivity.

Photoelectrons were shown to be sensitive tools for ultrahigh-sensitivity near-field probing [1-3]. We have shown that using this technique, plasmonic field enhancement can be experimentally measured with unprecedented surface sensitivity with the help of photoemitted and rescattering electrons [2]. It was demonstrated that the cutoff region of these photoelectron spectra is made up of electrons emitted from plasmonic hot spots of the nanoparticles [1]. If we use femtosecond pulses made up of ~1.5 eV photons for this measurement, the photoelectron generation is highly nonlinear and it can serve as a basis for time-resolved probing of near-fields in a spatially highly selective manner. In contrast to a previous experiment [3], by filtering for a certain kinetic energy range of photoemitted electrons, we can limit the measurement for rescattering electrons resulting in a sub-nm surface sensitivity [2] and selectivity for plasmonic hot spots.

2. Experimental results

To realize this novel concept, we built an ultrabroadband interferometric autocorrelator which was illuminated by 5.5-fs pulses of a Ti:sapphire femtosecond laser oscillator (Fig. 1a). The output of the interferometer was focused onto plasmonic nanoparticles and photoelectron spectra were recorded for a set of delays of the interferometer arms. By filtering for the highest electron kinetic energies, we could establish autocorrelation functions of the hot-spot field evolution of plasmonic nanostructures both for resonant and off-resonant cases. A representative plasmon-field autocorrelation curve is shown in Fig. 1b.

By considering the third-order nonlinearity of the photoemission process for most photons in the laser spectrum, we could reconstruct the plasmon-field autocorrelation curve and demonstrate that even the plasmon oscillation decay after the ultrafast excitation is in the sub-10-fs range under these extreme conditions.

3. Conclusions

By establishing this ultrafast time-resolved characterization technique, the buildup and decay of collective electron oscillations can be investigated with unprecedented spatiotemporal resolution and plasmonic
nanoparticles can be tailored for ultrafast optics applications such as near-field-enhanced high harmonic generation, near-field spectroscopy and many more.

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References


Fabrication of ultrathin multilayer structures and their characterization

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Abstract
Multilayer structures have been in the focus of research for decades. They exhibit various optical properties starting from anti-reflection coating, Bragg gratings and finishing with hyperbolic metamaterials. Meantime they accept quite simple theoretical analysis and straightforward modeling. In spite of such intensive study there are still numerous questions about quality of fabrication processes, accessible parameters ranges and adequate models accurately explaining their performance. We report on our activity in fabrication of ultrathin dielectric and metal-dielectric layers, and their characterization.

1. Introduction
We report on fabrication routines that allow us to prepare multilayer periodic stacks of exceptional quality in terms of their uniformity and reproducibility. We deposited smooth gold films of thickness from 5 nm to 10 nm on top of non-metallic aminosilane adhesion layer (APTMS) using DC sputtering deposition technique. Following characterization showed that the gold films with APTMS adhesion layer give better performance in comparison to gold deposited on typical metal (Cr or Ti) adhesion layers or no adhesion layer at all in terms of good surface roughness. Optical properties were also the closest to theoretical predictions [1].
The next fabrication step was to develop the technique for obtaining gold and dielectric multilayer structures. This step required optimization of deposition of ultra-thin aluminum dioxide (Al₂O₃) films in the range of 6-10 nm on top of APTMS using atomic layer deposition (ALD). We managed to fabricate stacks with up to ten periods. Remarkably, the roughness of the tens-period sample was very close to the roughness of just one layer. The samples were characterized in the visible and near infrared wavelengths, and their performance is similar to what is expected from hyperbolic metamaterials when exceeding certain amounts of periods [2].
To overcome notorious limitations of conventional effective medium approximation, we developed a nonlocal homogenization procedure [3,4]. The corresponding effective medium is considered as a waveguide-like slab with a finite thickness supporting propagation of modes specific to hyperbolic metamaterials. Consequently, two kinds of bulk propagating modes in the slab are distinguished and named as short-range and long-range propagating modes. The developed dispersion relations properly explain the cutoff conditions and number of modes in any arbitrary multilayer stack. Transfer matrix method and experimental characterization of gold-alumina multilayer samples ascertain the results of developed theory. Further basing on the mode-resolved effective medium approximation [4] we looked on a photonic local density of states (LDOS) and energy flow directionality of finite thickness multilayer slabs. This question is related to the LDOS enhancement through coupling of a quantum emitter to the bulk modes of the multilayer slabs. Indeed as expected LDOS is dependent on the number of periods in the stack as well as on position of the emitter. In both positions, the metal-dielectric slabs having smaller number of periods exhibit stronger emission rate enhancement near the transition wavelength to the hyperbolic regime. Furthermore, some modes show lower coupling angles for directional emission of the coupled quantum emitters [5].

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References


Nanophotonic systems for image processing

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Abstract
Conventional all-optical image processing requires relatively bulky optics limiting its potential use in mobile electronic systems. Here, the use of nanoscale resonant gratings and other thin film structures for image processing of both amplitude and phase objects is presented.

1. Introduction
The manipulation of images, for example, enhance the appearance of edges, remove noise or visualize phase gradients is ubiquitous in contemporary electronics. Digital methods are commonly used taking advantage of efficient algorithms and specialized imaging sensors, leading to their widespread use in applications including machine vision, remote sensing and microscopy. The increasing amount of data required in many of these applications, however, is accompanied by corresponding increases in energy consumption, the time required to process images and the bandwidth necessary to transmit data from location to location. Furthermore, images obtained by conventional cameras do not capture information about phase variations within an optical field arising from, for example, wavefront distortions associated with propagation through turbulent media and transmission through transparent objects such as cells. Prior to the advent of computational image processing, all-optical spatial filtering systems capable of real-time manipulation of both amplitude and phase images had attracted widespread attention. The bulky nature of these systems, however, mean that they are incompatible with the drive to miniaturization of digital systems. The emergence of meta-optical and other nanophotonic systems, however, provides an opportunity to develop compact all-optical systems capable of real-time image processing. This presentation discusses plasmonic systems for enhancing contrast of both amplitude and phase images.

2. Nanophotonics, thin films and image processing
Conventional all-optical image processing requires the introduction of so-called spatial filters into the Fourier plane of an image accessed by a lens. A second lens recovers the processed image. These spatial filters can modify the amplitude and/or phase of the angular spectrum of the image under consideration. The use of lenses and the required propagation distances leads to a system with dimensions typically of the order of centimeters. In 1979 Case [¹] presented a volume grating capable of edge enhancing an image when placed in the object (rather than Fourier) plane of the image. In this work it was noted that the choice of the object plane was somewhat arbitrary and that there was significant flexibility in choosing the location of device. Here we revisit this concept, building on recent advances in nanophotonics and the development of metasurfaces with a view to extending this approach to more complex processing including the visualization of phase gradients.

2.1. Device design
The key to designing these spatial frequency filtering devices is to recognize the one-to-one correspondence between the angle of incidence of a plane wave and the $x$- and $y$-components of the projection of its wavevector onto the plane of the device – its spatial frequency components $k_x$ and $k_y$.

We have previously investigated reflection devices based on thin films [²] and the excitation of bound modes in the continuum [³,⁴]. Utilizing coupling into cross-polarized states of the transmitted field, we have also investigated devices with both symmetric [⁵] and asymmetric [⁶] responses to spatial frequency.

Figure 1: Schematic showing device under consideration.

The device considered here consists of an array of silver patches on a thin film of TiO$_2$ supported by a glass substrate and coated with PMMA. A schematic is shown in Figure 1. The structure is designed to enhance sharp features and strong gradients in an incident amplitude or pure phase field at a wavelength of 578 nm. A period of 350 nm and a TiO$_2$...
thickness of 100 nm were chosen. The square silver nanoparticles had transverse dimensions of 210×210 nm and a height of 40 nm. Transmission images were obtained of samples placed directly onto the device illuminated with a filtered supercontinuum source (Fianium SC-450-2 with Superchrome VIS-FDS-MM filter) producing light with a bandwidth of approximately 5 nm. Figure 2 shows (a) the Fourier plane image of the device at a wavelength of 578 nm. The suppression of transmission of low spatial frequencies (i.e. plane waves at or near normal incidence) is apparent.

Figure 2: Experimental demonstration of edge enhancement of an amplitude image showing suppression of low spatial frequencies using a device with a period of 350 nm. (a) Shows a Fourier plane image showing transmission through the device at a wavelength of 578 nm. Images of a binary amplitude object at a wavelength of 578 nm taken through the device (b) and an unpatterned region of a glass slide (c).

The scale bar is 10 μm.

Figure 2(b) shows a preliminary image of a binary amplitude object (USAF test pattern) placed on the device. Compared to an image taken when the object was placed on a glass slide (Figure 2(c)), the background in the image is substantially reduced and edges enhanced.

To demonstrate the potential application of a compact chip device with these properties, Figure 3 shows images of filamentous algae in pond water placed on the device obtained at wavelengths of (a) 550 nm, (b) 578 nm, and (c) 600 nm. The suppression of the low-spatial frequency background is apparent in Figure 3(b).

Figure 3: Images of filamentous algae taken at (a) 550 nm, (b) 578 nm and (c) 600 nm.

3. Conclusions
The results of preliminary measurements and images obtained from the device presented here demonstrate the considerable potential of this approach for image manipulation. Advances in the development of simple quasi-analytic approaches to device design and recent experimental and computation results will also be presented.
Arbitrary Order Exceptional Point Induced by Photonic Spin-Orbit Interaction

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Abstract

Exceptional points in non-Hermitian systems have many intriguing properties and novel applications. High order exceptional points normally require delicate variations of multiple parameters and are difficult to achieve. In this talk, we will show that photonic spin-orbit interaction can induce exceptional points of arbitrary order without tuning any parameters.

If a Hamiltonian is non-Hermitian, its eigenvalues are complex in general. Tuning the non-Hermiticity can make multiple eigenvalues coalesce at one point, which is called an exceptional point (EP). Exceptional points possess many interesting properties with novel applications \cite{1, 2}. High order exceptional EPs have rich physics and have attracted considerable attention recently. Achieving high order EPs, however, is challenging since it normally requires tuning of multiple system parameters. We demonstrated a mechanism to achieve arbitrary order EPs in a simple system of coupled dipole resonators \cite{3}. The model system is shown in Fig. 1(a), where two spherical resonators locate on a waveguide. The spheres support chiral dipole modes, which couple with each other via the evanescent field of the guided plasmon. The coupling is unidirectional due to transverse spin-orbit interaction. The system can be described by a Hamiltonian:

\[
H = \begin{pmatrix}
\omega_0 - \frac{i}{\Gamma} (\gamma_1 + \gamma_2) & 0 \\
\kappa_{21} & \omega_0 - \frac{i}{\Gamma} (\gamma_2 + \gamma_3)
\end{pmatrix},
\]

The Hamiltonian has two eigenvalues coalesce at \(\omega_0 = \omega_0 - i\Gamma/2\), where \(\Gamma = (\gamma_1 + \gamma_2 + 2\gamma_3)/2\), corresponding to an EP. As shown in Fig. 1(b), at the EP, the Lorentzian shape of \(p_1\) (blue line) remains unchanged, while the resonance profile of \(p_2\) (red line) exhibits a destructive interference. Variation of the coupling distance will only affect \(p_2\) but not \(p_1\).

Higher order EPs can be easily achieved by adding more resonators on the waveguide. In the case of \(N\) resonators, the Hamiltonian is a diagonal matrix with a single eigenvalue \(\tilde{\omega}_0\) of algebraic multiplicity \(N\), representing an EP of order \(N\). We show that the system can give rise to spin-dependent energy cascade effect and the enhancement of sensitivity to external perturbations at the EP. We conducted experiments at microwave frequencies using high-dielectric spheres on a dielectric waveguide, the results of which agree well with the theoretical results. Our results provide an easy way to control the emission of coupled dipoles using the spin of light. The proposed system can serve as a convenient platform to study light-matter interactions at exceptional points.

Figure 1: (a) Schematic of the model system. (b) Dipole moments of \(p_1\) (blue line) and \(p_2\) (red line) at EP.

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References

Phase Mapping of the SPP-Coupled Nanoparticles by Angle-Resolved Cathodoluminescence

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Abstract

Nanoscale gaps between metals can strongly confine electromagnetic fields that enable efficient electromagnetic energy conversion and coupling to nanophotonic structures. In particular, the gap formed by depositing a metallic particle on a metallic substrate produces coupling of localized particle plasmons to propagating surface plasmon polaritons. Here we demonstrate the experimental visualization of the phase associated with the plasmonic field of metallic particle–surface composites through nanoscopically and spectroscopically resolved cathodoluminescence using a scanning transmission electron microscope.

1. Introduction

Plasmons, the collective electron oscillations in conducting materials, can produce extremely focused electromagnetic fields on the nanoscale, which are well known to pile up in nanogaps between two metallic structures. Although the proper control of such nanogaps is generally not trivial because of their strong dependence on the detailed surface morphology, a simple and relatively controllable system consists of an individual metallic nanoparticle separated from a metallic planar substrate by a nanoscale gap of a precisely determined distance. In the design of applications of such nanogap antennas, knowledge of near- and far-field distributions including the field phase is essential to engineer an efficient coupling between SPPs and propagating waves. We propose a general methodology to access the phase associated with the interaction of SPPs with a nanostructure placed on a SPP-supporting metal surface. Our method is based on the interference between light that is directly emitted from the planar surface upon electron impact and light resulting from SPPs also generated by the electron and subsequently out-coupled by the nanostructure; such interference is determined by measuring the resulting cathodoluminescence (CL) signal. (See Figure 1a.)[1-3] Because of its high combined spatial and spectral resolution, angle-resolved CL appears as an ideal tool that can potentially access the phase of photonic fields through interference. Here we visualize both near- and far-field distributions through CL performed on a scanning transmission electron microscope, allowing us to obtain the scattering phase associated with the interaction of SPPs with individual metallic nanoparticles.

2. Method

Figure 1 illustrates the phase extraction scheme and the measurement setup using a scanning transmission electron microscope. The phase information is retrieved through the interference of the scattered signal and the transition radiation, which are both coherently excited through electron impact on the metallic substrate. The sample we used is a silver sphere deposited on a silver substrate coated on a thin silica layer.

![Figure 1](attachment:image.png)

Figure 1: (a) Illustration of extraction of the SPP scattering phase through CL with the reference of transition radiation (TR). (b) Illustration of the angle-resolved cathodoluminescence setup. [3]
3. Results and Discussion

3.1. Mode identification

We first determined the optical modes of individual metallic spheres coupled to a metallic substrate by measuring particles with different sizes with the electron beam close to the particle and integrating the signal from all the angles, in order to avoid the interference effect. We identified bonding and anti-bonding dipoles of the particle due to the coupling to the metallic substrate, both in parallel and perpendicular to the substrate. These observed modes and their spatial symmetries are confirmed by finite element method (FEM) simulation, as shown in Figure 2.

![Figure 2: FEM simulations with electron beam excitation for a 160 nm sphere on a 10 nm SiO2/Ag substrate. (a,b) Simulated CL line-scan profiles with p- (a) and s- (b) polarizations. The sphere edges are indicated by vertical dashed lines. (c,d) Out-of-plane z-component plots with fixed electron beam position and orientation indicated by a purple line in panel (c).][3]

3.2. Phase extraction by interference

The spectroscopic line profile detected at a certain angle gives interference patterns, which directly give the phase of the nanoparticle scattering excited through SPP with respect to the phase of TR. The interference patterns can be well reproduced by introducing the phase of a coupled oscillator model with normal mode splitting. It is also possible to extract the dispersion relation of SPPs. We also try to visualize the phase distribution of the in-plane dipole by choosing an appropriate detection angle and polarization. This can be done by conformally mapping the observed SPP interference pattern considering the interference distance and the dispersion relation of the SPP. Figure 3 shows the retrieved SPP phase mapping of the nanoparticle placed on a metallic substrate. Patterns of an in-plane dipole along the horizontal direction (defined as the y axis in the figure) can be clearly seen at the photon energies between 2.2-2.6 eV where the in-plane dipole mode is dominant. At the lower photon energies, perpendicular dipole starts to dominate the pattern, and at the higher photon energies, some trace of the quadrupole pattern can also be found.

![Figure 3: CL interference pattern showing the phase map retrieved from the measurement with the polarization angle $\alpha = 65^\circ$ and detection angle $\theta = 75^\circ$ [3]. The scale bar corresponds to 500 nm in the conformal space.][3]

4. Conclusions

We have demonstrated interference measurements of silver spheres coupled to a metallic substrate using a STEM-CL setup, where strong fields are produced at the gap between the particle and the substrate. Because of coupling to the substrate, the dipole mode of the silver particle splits into antibonding and bonding modes with opposite induced surface-charge schemes. These split modes and their interaction with the surface are well reproduced by numerical electromagnetic simulations with the electron acting as a source.

Acknowledgements

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References


High refractive index contrast meta-surfaces for sensing and emitting devices

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Abstract

High contrast meta-surfaces support several optical eigenmodes, and the interference of the excited modes provides the extraordinary optical properties. We experimentally have demonstrated unique ultraviolet and blue-violet devices with high contrast meta-surface, such as a highly polarized ultraviolet light-emitting diode with very low loss and highly sensitive refractive index sensor with very simple optical system operating blue-violet wavelength.

1. Introduction

Meta-surfaces, which are subwavelength periodic structure, provide new way of photon engineering because of its artificially designable optical characteristics. In particular, high contrast meta-surfaces (HCM) composed of periodic high refractive index materials and low index surroundings are more attractive for many applications owing to its extraordinary optical properties, such as high reflectivity with ultra-broadband, high-Q-resonance, and anomalous diffraction [1]. The high contrast of the periodic refractive index supports not only the fundamental optical eigenmode but also the higher modes in HCM while the low contrast cannot. The excited several modes interfere each other at the top and bottom boundaries of the HCM. Owing to the interference, the optical properties of HCM can be artificially designed by its appropriate structural geometry. This can provide new device platform, such as tunable laser [2], high reflectivity mirror [3,4], polarizer with low aspect ratio [5], planer meta-lens [6], polarized light-emitting diode [7-9] polarization dependent mirror [10,11], high efficiency flexible color filter [12], highly sensitive refractive index sensor [13,14], and bio-sensor [15]. In this paper, we have proposed to apply HCM for ultraviolet (UV) and blue-violet wavelength region and demonstrated unique emissive and sensing devices operating at the wavelengths.

2. Emissive and sensing applications with high contrast meta-surfaces

We demonstrated highly polarized GaN-based UV-light-emitting diode (LED) incorporating Silicon (Si)-HCM (Si refractive index = about 4 at UV region) with low refractive index under layer. Highly polarized UV-LED is very suitable for many applications, for example inducing anisotropy of polymers. It is necessary to control the LED polarization property because the conventional GaN-based UV-LED generally shows unpolarized emission. However, most of UV emission is absorbed in polarizer, and it is difficult to realize high polarization selectivity with low loss in UV region.

![Figure 1: The emissive and sensing devices with HCM](image)

(a) Highly polarized GaN UV-LED with low loss
(b) Highly sensitive refractive index sensor with very simple optical setup

To overcome the issue, we utilized the interference between eigenmodes in Si-based HCM (Fig. 1(a)). The Si-HCM was fabricated on the top of the LED. Low refractive index layer (SiO₂ layer) was also inserted between the LED and the Si-HCM to maintain the subwavelength condition because the wavelength in the LED became shorter than that in air owing to high refractive index of GaN (the value = about 2.6 at UV region). We measured p- and s-polarization electroluminescence (EL) spectra of the LED (E-fields of each polarizations are shown in Fig.1 (a) as red and blue arrows). The EL spectra indicated that the eigenmode interference in Si-HCM highly suppressed the s-polarized emission whereas the p-polarized emission highly transmitted, and the polarization degree of the emission reached to 88% at a 370 nm wavelength. Moreover, p-polarized EL intensity is 1.2 times greater than that without
HCM. These results highly polarized UV-LED was experimentally demonstrated without the decreasing UV emission intensity.

We also demonstrated refractive index sensor using HCM operating at blue-violet wavelength region. Refractive index sensing technique is of great use for gas and bio-sensors. For these applications, high sensitivity and high chemical stability are desirable.

We successfully demonstrated highly sensitive refractive index sensor with very compact and high chemical stability using GaN-based HCM (Fig. 1(b)). The interference condition is considerably influenced the ambient around the HCM because the phase and amplitude of the modes significantly depend on the refractive index contrast between HCM and surrounding material. A GaN was selected as HCM material owing its high index value of refraction and extreme high chemical stability. We also selected the incident wavelength of around 400 nm, which has very low absorption in water, because the refractive index sensing applications are often used in aqueous environments. The GaN-HCM was fabricated on the top of GaN substrate using ion etching techniques. The peak in reflection spectra resulting from the modes interference was obtained at the wavelength of 415 nm with very simple normal incidence. The peak intensity significantly decreased with the increasing the surrounding refractive index n, from 1.333 to 1.346. These results mean our sensor detects refractive index of $6.3 \times 10^4$ with very simple optical system. The high sensitivity, compactness, and simple setup of our sensor are suitable for practical use of refractive index sensor.

Conclusions
In our presentation, we explain and discuss the theoretical and experimental details of our devices mentioned above. Moreover, we also show our latest research results related with HCM in this presentation.

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References
Flat Nonlinear Optics with Intersubband Polaritonic Metasurfaces

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Abstract

In this work we report electrically tunable nonlinear response and giant nonlinear circular dichroisms based on intersubband polaritonic nonlinear metasurfaces. Experimentally we achieved 0.75 μm of the second harmonic generation spectral peak tuning and over 86 % of nonlinear circular dichroisms around 10 μm wavelength.

1. Introduction

Nonlinear response from metasurfaces have opened a new direction in research such as generating new light sources, nonlinear holography, and nonlinear optical switching and modulations, to name a few, based on their significantly relaxed phase matching constraint and properties to control the local nonlinear response at the subwavelength scale [1]. To extend the utility of flat nonlinear optics, metasurfaces providing new functionalities such as broadband giant nonlinear response for efficient frequency conversion or giant nonlinear circular dichroisms for nonlinear frequency mixing need to be developed. It is well known that intersubband transitions in n-doped multiple-quantum-well (MQW) structure can be used to design nonlinear materials with giant 2nd and 3rd order nonlinearities up to 4-5 orders of magnitude larger than in traditional bulk nonlinear crystals. Recently, nonlinear metasurfaces with record-high nonlinear optical response up to 1.2×10⁹ m/V for second harmonic generation (SHG) and 4.4×10¹⁴ m²/V² for third harmonic generation (THG) based on coupling of electromagnetic modes in plasmonic nanoresonators with quantum-engineered intersubband nonlinearities in MQW structure have been demonstrated [2-4].

In this work, we propose and experimentally demonstrate two of key features based on the intersubband polaritonic nonlinear metasurfaces. One feature is an electrically tunable giant 2nd order nonlinear response based on combining of plasmonic resonators with Stark-tunable intersubband nonlinearities of MQW structure in which the intersubband transition energies are tuned by bias voltages applied on the MQW layer. Second feature is giant nonlinear circular dichroisms for SHG and THG based on combining the giant 2nd and 3rd order nonlinearities of MQW structure with C3 and C4 chiral meta-atoms for the SHG and THG, respectively.

Figure 1. (a) conduction band diagram of the MQW structure. (b) Calculated 2nd order nonlinear susceptibility as a function of DC bias voltages from -4V to +4V. (c) Fabricated metasurface. (d) Measured normalized conversion efficiency and the maximum conversion efficiency as a function of DC bias voltages.

2. Device design and experimental results

2.1. Electrically tunable SHG from Intersubband Polaritonic Metasurfaces

For broadband SHG in the mid-infrared region, a 400nm-thick nonlinear MQWs layer that contains 20 repetitions of the In₀.⁵³Ga₀.⁴⁷As/Al₀.⁵³In₀.⁴⁷As coupled-quantum well structure was grown by the molecular beam epitaxy on a semi-insulating InP substrate. One period of the MQW structure shown in Fig. 1(a) consists of three quantum wells in which the intersubband transition energies between electron subbands for 1-2 and 1-3 can both be modulated for bias voltages through quantum confined Stark effect. The modulated intersubband transition energies in the MQW lead to spectral shift of the 2nd order nonlinear response of the MQW as shown in Fig. 1(b). The MQW structure has the maximum 2nd order nonlinear
susceptibility of 300 nm/V for SHG at the pump wavelength of 9.8 μm and it can also produce a giant nonlinear response over 200 nm/V in the 8.5 to 10.5 μm wavelength range by applying bias voltages.

To achieve efficient SHG, the MQW layer is sandwiched between a metal ground plane (bottom contact) and a patterned array of complementary V-shape nanoantenna. Complementary V-shaped nanoresonator was designed to induce the enhanced local $E_x$-field in the MQW layer at both fundamental frequency (FF) $\omega$ and SH frequency $2\omega$ for $x$- and $y$-polarized input beam, respectively, resulting in the highest effective nonlinear susceptibility for $yxx$ polarization combination.

For experimental demonstration, we fabricated a 100μm × 100μm 2D array of the nanoresonators structure (Fig. 1(c)). For nonlinear characterization, a pulsed broadly-tunable QCL pump source ($\lambda_{ee} \approx 8.1$ to 11 μm) and an InSb detector were used. Fig. 1(d) show measured SHG conversion efficiency curve as a function of the input pump wavelength under the different bias voltages from -4V to +4V with 1V step. Each SHG conversion efficiency curve was normalized with its maximum conversion efficiency value (left y-axis of Fig. 1(d)) and the maximum SHG conversion efficiency corresponding to each bias voltage is indicated by a dot (right y-axis of Fig. 1(d)). As the voltage is changed from +4V to -4V, it was clearly found that the peak wavelength of the SHG conversion efficiency curve is tuned from 9.64 μm to 10.49 μm and the maximum conversion efficiency is maintained above 2×10^{-3} %.

### 2.2. Giant SHG and THG nonlinear circular dichroisms

Using the same MQW structure shown in Fig. 1(a), the metal-insulator-metal plasmonic structure was used where the top metallic nanoantennas were designed to obtain giant circular dichroism (CD) with C3 and C4 rotational symmetries for SHG and THG, respectively. Fig. 2(a) shows schematic of the nonlinear metasurface with the C3 and C4 chiral meta-atoms integrated on the same chip for chiral harmonic generation for SHG and THG. The plasmonic nano-resonators were designed to obtain maximum CD value around at the pump wavelength of 10.5 μm.

For nonlinear characterization, we used the same QCL pump, the InSb detector, and proper quarter wave plate (QWP). Fig. 2(b) and (c) respectively show the experiment results of the normalized intensity of SHG and THG signal from chiral metasurface at a fixed power of input pump for the RCP and LCP input pump beam. As shown in the data, large SHG and THG signal differences were obtained for the two circular polarized input pump beam for the wavelength range above 9.4 μm and the signal difference was maximized around the optimized design wavelength of 10.3 μm. To quantify the measured nonlinear chiral responses, CDs for SHG and THG as function of the wavelength of input pump were calculated using the measured data and the result is shown in Fig. 2(d). The black and red line respectively indicate the CD values for SHG and THG. The maximum nonlinear CD value over 0.86 for both SHG and THG was achieved and over 0.5 of CD values were obtained from both structures in broad wavelength range from 9.7 μm to 10.9 μm.

### 3. Conclusions

Based on combining giant 2nd and 3rd order nonlinearities of the MQW structure with properly designed plasmonic nanoresonators, we experimentally achieved electrically tunable SHG nonlinear response and giant nonlinear circular dichroisms for the SHG and THG. The two features proposed in this work may be open a new pathway in designed flat nonlinear optics for various applications such as broadband nonlinear light source, nonlinear holography, and nonlinear optical modulations.

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**References**


Nonlinear and electro-optic nanostructured metal-oxides

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Abstract
Non-centrosymmetric metal-oxide media possess a plethora of functional optoelectronic properties like second harmonic generation, electro-optic and electro-mechanical response. We present a variety of approaches to exploit these mechanisms at the nanoscale with the use of all-dielectric metasurfaces and photonic crystals based on barium titanate as well as plasmonic metasurfaces based on gold-barium titanate nanostructures.

1. Introduction
Metal oxides that lack an inversion symmetry center are responsible for several optical nonlinear effects due to the high value of the second-order susceptibility tensor while their electro-optical and electro-mechanical properties have led to commercial electro-optic modulators and actuators, respectively. [1] The plethora of properties this type of materials hold, heralds the promise of highly integrated optoelectronic devices on a single chip. [2] Barium titanate (BaTiO₃, BTO) is a metal-oxide ferroelectric material, which is transparent from the near UV to the infrared range, has high second order susceptibilities, strong electro-optic coefficient [3] and piezoelectric properties, mostly known for bulk materials. Nanostructured media like photonic metasurfaces and photonic crystals provide a platform that improves optical nonlinearities and electrical-to-optical modulation in comparison to bulk crystals. [4]

Here, we harness the versatile properties of BTO to report on the second harmonic generation from all-dielectric metasurfaces and photonic crystals, as well as the electrical-to-optical modulation of plasmonic metasurfaces hybridized with BTO via the linear electro-optic effect and the electromechanical effect.

2. Results and Discussion
2.1. Non-linear all-dielectric BTO metasurfaces
We develop a new type of nonlinear metasurface based on BTO and demonstrate an efficient nonlinear optical response over a broad spectral range, from near-ultraviolet to the visible range. Metals and semiconductors used for second order processes typically have losses in this spectral range. Compared to previously demonstrated nonlinear plasmonic metasurfaces, these BTO metasurfaces show less sensitivity to surface roughness. Furthermore, their optical nonlinearity stems from the noncentrosymmetric crystal structure of the BTO. We prepare arrays of BTO nano-disks with fixed radius of 160 nm and different periods from 400 nm to 600 nm using a top-down electron lithography fabrication approach of a BTO thin film obtained by pulsed laser deposition. In Fig. 1a is presented the SEM image from a part of the dielectric metasurface array. We measure the polar plot of the SHG signal from a sample of 600 nm period for different excitation wavelengths, Fig. 1b. We demonstrate an enhanced SHG conversion efficiency from the all-dielectric BTO metasurfaces in the NUV and visible range compared to the original unpatterned BTO layer, while we tune the SHG enhancement and SHG radiation pattern by the period of the BTO metasurface. [5]

2.2. Three-dimensional BTO photonic crystals (PhC).
One of the potential candidates for enabling photonic circuits are three-dimensional (3D) nonlinear PhC. We use a bottom-up fabrication technique (UV-soft nanoimprint lithography) together with solution processing of BTO nanoparticles to create large-scale 3D nonlinear woodpile PhC. The woodpile structure has the advantage among other PhC structures, by that it can be fabricated layer by layer. It is therefore suitable for roll-to-roll fabrication, which can be easily adapted in industry. The surface areas of the prepared photonic crystals with up to eight layers are 1.0 cm². Polarization-dependent second harmonic generation measurements together with their diffraction patterns prove a cubic PhC structure in the linear and nonlinear regime. In Fig. 1c, the SEM image of an 8-layer woodpile structure is shown together with its SHG polarization responses at four different excitation wavelengths (Fig. 1d). [6]

2.3. Electro-optic (EO) plasmonic metasurfaces
A novel type of solution processed thin films made of BTO nanoparticles are used to coat a subwavelength periodic array of gold (Au) nanowires and exploit the electro-optic response of BTO nanoparticles, as shown in the SEM image of Fig. 1e. Reflection changes of 0.15% for a 3.5 Volts (V) control signal for modulation frequencies from 500 kHz up to 20 MHz are recorded, in the near-infrared. The electro-optic response shows a hysteretic behavior upon the application of an offset DC field, (see Fig. 1f), while the electro-optic coefficient of nanoparticle films is estimated to
2.4 Electro-mechanical (EM) metasurfaces

Solution processed thin films made of BTO nanoparticles are used to coat a subwavelength array of gold (Au) nanowires. Under electrical stress, BTO nanoparticles form assemblies of cantilevers, which are delaminated from Au nanowires due to the EM force. After this process, several BTO cantilevers can move freely anchored on the sides of the sample, see SEM in Fig. 1g. The motion of the cantilevers perturbs the near field of the plasmonic nanowire array, which lead to reflectivity changes up to 3%. The magnitude of the optical modulation is controlled by the DC applied electric field on the samples, see Fig. 1h. From finite element method simulations, the first in-plane vibration mode of a 40 μm cantilever is located at 293 kHz, close to the experimental maximum modulation frequency of 290 kHz. The EM response reported for first time here in nanoparticle-assembled cantilevers can have application in different types of mass, gas or force sensing.

3. Conclusions

We showed that BTO nanostructures such as metasurfaces or photonic crystals can play a key role in highly integrated optoelectronic networks. Applications ranging from nonlinear optics and electro-optic modulators for intrachip or interchip optical interconnects to nano-mechanical actuators show the diversity of functions the metal-oxides have.

References

Acoustic Graphene Plasmons under a DC bias

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Abstract

It has been shown that in a graphene/insulator/metal structure, the plasmons acquire a linear dispersion whose sound velocity is very near the Fermi velocity in graphene. I show that a DC current causes a redshift of the acoustic plasmons travelling upstream in the direction of which electrons flow. As the redshift of the upstream branch causes acoustic plasmon to approach the particle-hole continuum, the spectral weight of this plasmon branch is substantially reduced, resulting in a near unidirectional plasmon.

1. Introduction

Graphene surface plasmons provide an ideal tool for applications in the terahertz range, primarily due to their long lifetime, the strong field confinement, and their extreme tunability with an external gate. The field confinement can be further enhanced in graphene/insulator/metal structures in which the distance $d$ between the graphene and metallic gate becomes small, resulting in a linear dispersing acoustic plasmon.[1, 2] Understanding new ways to tune the sound velocity and other properties of the acoustic plasmons is thus of strong interest.

Here we discuss the effects of an external bias on the acoustic plasmons. We show that the DC bias causes the upstream (downstream) acoustic plasmon branch to redshift (blueshift), similar to previous studies on ordinary graphene surface plasmons.[3] As the upstream branch approached the particle-hole continuum, its spectral weight substantially decreases, resulting in an essentially unidirectional plasmon mode only possible in the graphene/insulator/metal system. We provide numerical results for the critical current as a function of the Fermi energy and the dielectric environment.

2. Polarization and Plasmons in a DC bias

Within the RPA approximation, the dynamical polarization in graphene is given by

$$\Pi(q, \omega) = \frac{q_s q_u}{2\pi} \sum_{s,s',x=\pm} \int d^2k \left[ f_{s,s'}(k, q) \times \left( \begin{array}{c} 1 + \frac{s' k + q \cos(\theta k - \theta q)}{|k + q|} \right) \right]$$

where $g_s(q_s) = 2$ is the spin (valley) degeneracy, $E_s(k) = s\hbar v_F k$ is the energy of the $s$th band, $v_F \approx 10^6$ m/s and

$$f_{s,s'}(k, q) = \frac{1}{2} \left[ 1 + \frac{s' k + q \cos(\theta k - \theta q)}{|k + q|} \right],$$

is the band-overlap integral. The equilibrium Fermi Dirac distribution function is given by

$$n_F(E) = \left( 1 + \exp \left( \frac{E - E_F}{k_B T} \right) \right)^{-1}.$$

In order to model the polarization in the presence of a DC bias, we use a simplified shifted Fermi surface model in which the Fermi surface is centered around a wave vector $k_s$ rather than $k = 0$.[4] For a shift in the $x$-direction, the Fermi wave number gains an angular dependence according to

$$k_F^x = k_s \cos(\theta) + \sqrt{k_F^0 - k_s^0 \sin^2(\theta)}.$$  \hspace{1cm} (4)

It is easy to see that $k_s$ is related to the applied electric field via $k_s = e E \tau / \hbar$, where $\tau$ is the transport lifetime in graphene. We substitute Eq. (4) for $k_F^x$ in the Fermi function, and determine the polarization using Eq. (1).

In a graphene/insulator/metal structure in which the graphene is separated from the metal by a distance $d$, the plasmons are defined by the solution of the equation

$$1 = U(q) \Pi(q, w),$$  \hspace{1cm} (5)

where

$$U(q) = \frac{e^2}{2\kappa \epsilon_0 q} \left( 1 - \exp(-2qd) \right),$$

is the Fourier transform of the Coulomb interaction in graphene, and $\kappa$ is the dielectric constant of the environment. Solving Eq. (5) with the polarization defined by Eqs. (1) and (4) allows us to determine the acoustic plasmon dispersion in the presence of a DC bias.

3. Results

In order to investigate our results numerically, we make use of the spectral loss function[5]

$$S(q, \omega) = -\text{Im}[1 - U(q) \Pi(q, \omega)]^{-1},$$

which measures the spectral intensity of the plasmonic modes. Our results are summarized in Fig. For comparison, we include the analytic approximation of the acoustic...
Figure 1: Loss function of the graphene/insulator/metal system for $E_F = 200$ meV, $d = 3\, \AA$, and (a) $k_x = 0$, (b) $k_x = 0.5k_F$ and (c) $k_x = 0.8k_F$. The black lines show the onset of the particle-hole continuum, while the red line shows the acoustic plasmon with a sound velocity defined by Eq. (8). We see that as the current is increased, the $-q$ branch is redshifted towards the particle-hole continuum and eventually disappears at large values of the current.

Plasmon modes in zero bias $\omega = c_s k$ where

$$c_s = v_F \sqrt{\frac{(1 + A)^2}{1 + 2A}}, \quad (8)$$

$$A = \frac{g_s g_v E_F}{2\pi (2v_F)^2} \frac{e^2 d}{\varepsilon_0}. \quad (9)$$

For $d = 3\, \AA$ and $E_F = 200$ meV, we find $A = 1.7$ and $c_s = 1.3v_F$. The numerical results of the loss function are shown in Fig. 1. We see that by the time $k_x = 0.8k_F$, the $-q$ branch has essentially zero spectral weight. In Fig. 2 we show the best linear fit for the $\pm q$ branch at fixed $E_F$. We see that there is a sudden decrease of the acoustic velocity of the $-q$ branch at a critical value of $k_x$, corresponding to the point in which the $-q$ branch disappears. We show in Fig. 3 this critical $k_x$ as a function of $E_F$. We see that the critical $k_x$, and thus the critical current, decreases substantially with decreasing $E_F$. This suggests that the non-reciprocity can be tuned by tuning the carrier density.

4. Conclusions

We have shown that a strong nonreciprocity of the graphene surface plasmons can be induced by a DC bias in graphene/insulator/metal structures. We found that the downstream branch exhibits a blue shift, while the upstream branch exhibits a redshift. As the upstream branch approaches the particle hole continuum, it’s spectral weight dramatically decreases at some critical value of the current. We show that this critical current substantially decreases with decreasing Fermi energy, suggesting it can be easily tuned with an external gate.

Figure 2: Acoustic plasmon velocity in a DC bias for $E_F = 200$ meV and $d = 3\, \AA$.

Figure 3: Critical $k_{sc}$ as a function of the Fermi energy $E_F$. We see that the critical current decreases by nearly a factor of 10 as the Fermi energy is reduced.
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References


Free-carriers nonlinearities in semiconductor plasmonics

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Abstract

We study free-carriers nonlinearities in highly doped semiconductors. We develop a theoretical model based on the hydrodynamic description of free-electrons expanding nonlinear terms up to the third-order. Because of small carrier densities in semiconductors compared to noble metals, hydrodynamic effects result strongly amplified. We show that contrarily to noble metals, in fact, free-electron nonlinearities in doped semiconductors can be several orders of magnitude larger than crystalline lattice nonlinearities.

1. Introduction

Semiconductor technology based on multi-quantum well nonlinearities have enabled the strongest nonlinear susceptibilities [1]. Their resonant nature however has hindered their application in practical devices, since it inevitably causes a slower response and increased decoherence. In recent years, highly doped semiconductors have been introduced as high-quality and tunable mid-IR plasmonic materials for integrated devices. The mid-IR frequency range is of notable interest for the chemical and biological identification of molecules for environmental, healthcare, and security sensing applications, since this range includes the so-called molecular fingerprint region with countless unique vibrational absorption lines.

Dynamic properties of doped semiconductors undergo an interesting transition from the size-quantization regime (quantum dots) to the classical regime of plasmon oscillations. This transition region, which can be defined by the size of the structures as well as the number of free carriers, can exhibit strong nonlocal and nonlinear optical response due to a large variety of electron-electron interactions. Free-electron nonlinearities are intrinsically nonlocal, in the sense that the induced currents depend not only on the value of the electric field at a given point but also, through their spatial derivatives, on the value of the fields in the surrounding area.

In noble metals, free-electron nonlinearities have been shown to strongly contribute to second-order processes [2]. Experimental measurements in gold nanoparticle arrays have demonstrated second-harmonic generation efficiencies comparable to nonlinear crystals when normalized to the active volumes [3]. In principle, however, the larger are nonlocal effects the larger is the free-charge nonlinear optical response, because the volume of the regions involved in the process are increased.

A measure, \( l \), of nonlocal effects can be linked to the ratio of Fermi velocity, \( v_F = \left( \frac{3\pi^2 n_0}{m} \right)^{\frac{2}{3}} h / m \), over the plasma frequency, \( \omega_p = \sqrt{\varepsilon_0 n_0 / (m\varepsilon_0)} \), with \( n_0 \) and \( m \) being the charge concentration and the effective charge mass respectively (\( \varepsilon, h, \) and \( \varepsilon_0 \) represent the usual physical constants). Leaving out all the constants, we ultimately obtain that \( l \sim v_F / \omega_p \ll 1 / \left( n_0^2 m^2 \right) \).

Because, both \( n_0 \) and \( m \) are much smaller in semiconductors than in noble metals, nonlocal and hence nonlinear effects are expected to be much larger. The charge density \( n_0 \) can be in fact three orders of magnitude smaller in semiconductors than in noble metals, and still retaining a plasmonic behavior at mid-IR frequencies. While the effective charge mass can be 10 times smaller. Hydrodynamic theories have been successfully used to describe the free-electron rich dynamics in noble metal systems and are then extremely relevant to describe the behavior of highly doped semiconductors.

2. Discussion

In the context of the hydrodynamic model, under the influence of external electric and magnetic fields, \( E(r,t) \) and \( H(r,t) \), for a nonmagnetic medium, the electron fluid density \( n(r,t) \) and the current density \( J(r,t) \) satisfy the following equation,

\[
\dot{J} + \gamma J = \frac{n e^2}{m} E - \frac{e\rho_0}{m} J \times H +
\frac{1}{e} \left( \frac{1}{n} \nabla \cdot J + J \cdot \nabla \frac{1}{n} \right) + \frac{e\xi}{m} n^{2/3} \nabla n,
\]

where \( m \) is the effective electron mass, \( e \) the electron charge (in absolute value), \( \gamma \) is the electron collision rate, \( \rho_0 \) is the magnetic permeability of vacuum and time derivatives are expressed in dot notation. The last contribution is due to the electron fluid pressure \( p_{TF} = \xi n^{5/3} \), here described within the Thomas-Fermi model, with \( \xi = \frac{\hbar^2}{4m} (3\pi)^{2/3} \).

Following a perturbative approach we can write \( n = \)
\[ \mathbf{p} + \gamma \mathbf{p} = \frac{n_0 e^2}{m} \mathbf{E} + \beta^2 \nabla \cdot (\nabla \cdot \mathbf{P}) + S^{(2)}_{NL} + S^{(3)}_{NL}, \quad (2) \]

where \( S^{(2)}_{NL} \) and \( S^{(3)}_{NL} \) are the second- and third-order nonlinear sources, respectively,

\[
S^{(2)}_{NL} = \frac{1}{m} \mathbf{E} \nabla \cdot \mathbf{P} - \frac{\epsilon_{\mu 0}}{m} \mathbf{P} \times \mathbf{H} + \frac{1}{\epsilon_{\mu 0}} (\mathbf{P} \nabla \cdot \mathbf{P} + \mathbf{P} \cdot \nabla \mathbf{P}) + \frac{1}{3} \beta^2 \nabla (\nabla \cdot \mathbf{P})^2, \quad (3)
\]

\[
S^{(3)}_{NL} = -\frac{1}{2 e^2 n_0^2} \left[ \nabla \cdot \mathbf{P} (\mathbf{P} \nabla \cdot \mathbf{P} + \mathbf{P} \cdot \nabla \mathbf{P}) + \mathbf{P} \cdot \mathbf{P} \nabla \nabla \cdot \mathbf{P} \right] - \frac{1}{27} \beta^2 \nabla (\nabla \cdot \mathbf{P})^3. \quad (4)
\]

In these equations, contributions up to the third order have been considered. The polarization vector \( \mathbf{P}(t) \) is related to \( J \) through \( \mathbf{P} = J \), and \( \beta^2 = \frac{\epsilon_{\mu 0}^{2/3}}{m} \).

In order to show the strength of nonlinear free-electron contributions compared to traditional bulk \( \chi^{(3)} \) nonlinearities, in Fig. 1 we show calculated third-harmonic generation (THG) efficiency from slabs made of Ge and InP with doping of \( 2 \times 10^{19} \) cm\(^{-3} \). Free-electron THG can be 5 and 7 orders of magnitude higher than bulk \( \chi^{(3)} \) THG, for Ge and InP respectively at 10 W/\mu m\(^2\) (1 GW/cm\(^2\)) pump peak intensity. The difference from Ge and InP is due mainly to the lower \( \chi^{(3)} \) value for Ge. In order to show the ideal potential of hydrodynamic nonlinearities we have calculated THG efficiency for a structured surface (not shown here) of doped Ge, which shows a deep resonance in the reflection spectrum around 11.6 \mu m. That is, approximately all the pump energy impinging on the structure is coupled inside the material. Such systems show conversion efficiencies of \( 10^{-5} \) with 1 W/\mu m\(^2\) (0.1 GW/cm\(^2\)) pump peak intensity. Note that such input intensities can be achieved by commercially available quantum cascade and compact fiber optics pulsed lasers.

3. Conclusions

Experiments of THG from doped Ge single plasmonic antennas have estimated conversion efficiencies of about \( 10^{-5} \) with input peak intensities of \( \sim 30 \) GW/cm\(^2\) [4]. This value is in line with theoretical efficiencies obtained from a slab of 0.7 \mu m in analogous doping and excitation conditions. Note however that such efficiencies cannot be accounted for by intrinsic \( \chi^{(3)} \) nonlinearities, since they are predicted to generate less than 1% of the measured signal. We have also successfully tested our model against other experimental results obtained with different materials, such as ITO [5].

References


Measurement of saturable absorption behavior of CNT/PDMS coated high-\(Q\) microcavity towards mode-locking of Er-doped laser

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Abstract

We developed a method for coating CNT/PDMS on a high-\(Q\) silica microcavity that allows us to obtain saturable absorption that is needed for building a microresonator based Er-doped mode-locked laser.

1. Introduction

Mode-locked erbium-doped fiber lasers that use carbon nanotubes (CNTs) as saturable absorbers have found various applications thanks to their ability to generate ultrashort optical pulses. Recently, there has been a growing demand for an increase in the repetition rate of such ultrashort laser pulse sources, which require a short optical cavity length [1].

The purpose of this research is to develop a mode-locked laser using a microcavity that has the potential to generate pulses with a repetition rate of several tens of GHz. As a first step, we develop a method for coating CNTs dispersed in polydimethylsiloxane (PDMS) on a high-\(Q\) silica toroid microcavity. Moreover, we describe saturable absorption measurement in a high-\(Q\) microcavity.

2. Fabrication of CNT/PDMS coated microcavity

We have already reported the saturable absorption of CNTs on a silica toroid microcavity grown on a cavity surface by using chemical deposition (CVD) [2]. However, it was somewhat challenging to control the quantity of CNTs with this method, which is critical if we want to develop a mode-locked laser. Here, we use a different approach, where CNTs are dispersed in the PDMS polymer and then coated on a microcavity. This approach is advantageous since we can control the quantity of CNTs, which means that we can precisely control the linear and nonlinear loss.

We start with ultrasonicated CNTs made in isopropanol with the HiPco method, where PDMS is added step-by-step to the solution thus allowing the viscosity to increase gradually. Then the isopropanol is slowly evaporated while the solution is kept at 70°C for 48 hours. Finally, the CNT/PDMS droplets are transferred to the fabricated silica toroid microcavity with the method shown in Fig. 1.

3. Optical measurement of CNT/PDMS coated microcavity

First, we confirmed that the \(Q\) is very high at 2.1\(\times\)10\(^7\) after coating the silica toroid with PDMS (w/o CNTs). The value drops to \(Q\sim\)10\(^6\) with 0.24 mg/ml of CNTs in PDMS, but this is still sufficiently high for our purpose. The \(Q\) value also agrees well with a simple model we developed.

Next, we have to ensure that the PDMS coating does not significantly influence microcavity dispersion. Figure 2(a) shows the calculated and measured dispersions of the microcavity. The dispersion of the PDMS coated silica toroid microcavity is the same as the calculated value we obtained where we assumed a bare cavity. This shows that the modulation of the dispersion is negligibly small even when we coat the cavity with PDMS.

Finally, we measured the saturable absorption (SA) of a CNT/PDMS coated microcavity with 0.24 mg/ml CNTs. We developed a CW pump-probe method, where the frequencies of both the pump and probes are simultaneously scanned, but at different sweep speeds (a slow sweep speed for the pump, and a fast sweep for the probe that measures the \(Q\)). This allows us to measure \(Q\) values at different coupling pump powers. The \(Q\) of the cold cavity is 1.3\(\times\)10\(^6\), where the value increases to 1.8\(\times\)10\(^8\) when the pump is coupled to the cavity. The result is summarized in Fig. 1(b), where clear SA is observed. The saturation intensity is 15 MW/cm\(^2\) and the modulation depth per round trip is 3.2\(\times\)10\(^{-3}\). These values are sufficient to achieve mode-locking.
4. Er doped microresonator

We used sol-gel method to fabricate an Er-doped microresonator. A 2.0-μm thick Er-doped silica film was deposited on a silicon wafer, where a toroid microresonator is formed by using photolithography, BHF wet etching, XeF₂ chemical vapor etching, and CO₂ laser reflow. The diameter of this resonator was about 70 μm, the Er ion concentration was 1.8×10¹⁸ cm⁻³, and the Q value was 2.0×10⁶ at 1480 nm wavelength.

When we pump the cavity at 1480-nm laser, multimode operation was confirmed at around 1550 nm wavelength, as shown in Fig. 3(a). The longitudinal mode spacing was about 10 nm, which is equal to the FSR of the cavity. The oscillation threshold was about 2.0 μW, and the oscillation efficiency was 1.5%.

The measured LL curves for two different Er concentration are shown in Fig. 3(b). When the concentration was changed from 0.85×10¹⁸ cm⁻³ to 1.7×10¹⁸ cm⁻³, the oscillation efficiency also increased from about 0.6% to about 1.0%.

Numerical calculation reveals (we will discuss during the presentation), that a larger diameter of about 300 μm is needed to achieve mode-locking. So, we also demonstrated laser oscillation in a resonator with a diameter of about 300 μm. For this purpose we grew Er-doped film with a thickness to about 3.0 μm. A successful laser operation will be shown in the talk.

5. Conclusions

In summary, we demonstrated the CNT/PDMS coating of a silica toroid microcavity and observed clear SA behavior, which is the first step towards the development of a mode-locked microcavity laser. We also demonstrate laser oscillation of Er doped silica toroid microresonator and will discuss about the required condition that is needed to achieve mode-locking.

Acknowledgements

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References


Fig. 2 (a) Simulated and measured dispersions. (b) Absorption coefficient of CNT/PDMS coated silica microtoroid in function to the pump intensity.

Fig. 3 (a) Multimode operation of Er doped silica toroid microresonator. (b) LL curve for different concentrations.
Acoustic metamaterial beam with a perfect bandgap based on a quadruple-mode resonator array

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Abstract

We introduce a metamaterial in the form of a rectangular cross-section beam made of a single isotropic material that can simultaneously suppress all elastic-wave polarizations, i.e. compressional, in-plane shear, flexural and torsional waves, over a range of frequencies around 1 kHz. This is experimentally achieved by machining replicas of a unit cell based on a planar resonator with interconnected ribs in an aluminum beam. Our method opens the way to various applications in easily-manufacturable vibration isolators and novel acoustic wave control.

1. Introduction

Solid geometries guide multiple acoustic waves of different polarizations, comprised of compressional and/or shear stresses. In case of rectangular cross-section beams and propagation along their length, acoustic-wave polarizations can take four different forms, i.e. compressional, shear-horizontal (i.e. in-plane shear), shear-vertical (i.e. flexural), and torsional modes. Suppressing such acoustic modes is an industrially important issue. In spite of recent remarkable progress in the field of acoustic metamaterials, there are still important unachieved requirements in applications involving metamaterial beam or rods, i.e. meta-beam or meta-rods, for vibration damping. Geometries with perfect bandgaps in a particular frequency range where no acoustic modes can propagate are suitable for strong dampers. Moreover, single-material structures are desirable for easy manufacturing. Perfect bandgap meta-beams/rods are often constructed by combining several materials [1-3], although some single-material phononic crystals with perfect bandgaps have been reported [4,5]. In this study, we demonstrate by simulation and experiment a single-material perfect-acoustic-bandgap meta-beam in the kHz frequency range [6].

2. Design and Simulation

A photograph of the metabeam is shown in Figure 1(a). The structure consists of an aluminum (dural A2017) plate of thickness 8.0 mm and width 80 mm with a periodic drilled pattern of square unit cells at a repeat distance 80 mm. The drilled sections are perpendicular to the top and bottom surfaces of the beam. Figure 1(b) shows a schematic diagram of a single unit cell of dimension 80 mm×80 mm. It consists of an outer frame and an inner geometry with a resonating inner mass supported by several interconnected ribs that function as springs [6].

The numerically derived dispersion relation

Figure 1. Metabeam design. (a) Photograph. (b) Schematic of the top view of the unit cell. The gray region is aluminum and the inner white areas are holes.

Figure 2. Acoustic dispersion relation for axial propagation in the metabeam. The curves correspond to compressional (C), shear-horizontal (SH), shear-vertical (SV), and torsional (T) modes, respectively.
calculated by COMSOL Multiphysics is shown in Figure 2, showing the existence of a perfect bandgap from 0.97 kHz to 1.09 kHz arising from local resonances where the bandgaps for the four modes overlap. Strikingly, in spite of the beam being able to guide four different acoustic polarizations, this structure damps out all of these axially propagating acoustic disturbances in the bandgap region.

3. Experiment

We measured the acoustic propagation characteristics for all four modes by means of a 10-unit-cell metabeam of length 80 cm. The sample is excited by a sinusoidally driven piezoelectric disk bonded on the end. Three-axis accelerometers are used at two points at both ends of the metabeam in conjunction with lock-in detection, in order to obtain a measure of the acoustic wave damping.

The experimental output/input amplitude ratio for all four modes is shown on a logarithmic scale in Figure 3. Outside the bandgap in each case, interference by multiple acoustic reflections occurs, producing local maxima and minima, but all modes show marked damping in the bandgap regions. The output/input ratio takes a value less than 0.5 between 1.02 and 1.16 kHz, which is in reasonable correspondence with the simulated perfect-bandgap region.

![Figure 3](image)

Figure 3. Experimentally observed output/input acoustic amplitude ratio for each acoustic mode. (a)-(d) correspond to the compressional, shear-horizontal, shear-vertical (flexural), and torsional modes, respectively. The vertical dashed lines indicate the band edges for each mode expected from the simulations, whereas the gray shaded region in each case corresponds to the perfect bandgap expected from the simulations.

4. Conclusions

We have demonstrated both experimentally and by simulation a lightweight single-metamaterial aluminium metabeam with a rectangular cross section in the form of a periodic quadruple-mode resonator array that displays a perfect acoustic bandgap near 1 kHz. In this region, our structure efficiently damps out compressional, in-plane shear, flexural and torsional vibrations, as predicted by the simulations. This result should open the way to new easily-manufacturable vibration damping structures and to new ways to control acoustic waves.

Acknowledgements

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References


Ultrafast THz Absorption Modulation in a Graphene-Based Thin Absorber

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Abstract

We study both experimentally and theoretically an ultrafast, optically tunable graphene-based thin film absorption modulator for operation in the THz regime. Graphene hot carrier generated by an ultrafast near-IR pulse, induce negative photoconductivity with a decay time of 2.79 ps. As a result, a modulation of 40% present in the THz absorption was demonstrated experimentally in the low THz regime [4]. However, an ultrafast dynamic control of the absorption properties of such devices as well as their response under simultaneous electrostatic gating remains a challenging task.

2. Results

Here we experimentally demonstrate a graphene based ultra-thin absorber capable to modulate the THz amplitude in the picosecond time scale upon near-IR photoexcitation [5] by affecting the terahertz conductivity in the graphene sheet. In detail, the optical signal leads to the degradation of the THz graphene conductivity.

1. Introduction

Graphene, the acclaimed two-dimensional (2D) material made of carbon atoms arranged in a honeycomb lattice, presents unique and exceptional mechanical, thermal, electrical and optical properties [1]. Particularly in the THz spectrum, graphene is considered a suitable platform for dynamically tunable metasurface components [2], exhibiting a Drude-like response due to its easily generated and controlled free carriers. Within the concept of metasurfaces, graphene thin film absorbers, are usually implemented by placing a graphene layer, uniform or with features, on the top of a dielectric film, which is placed on a perfectly conducting metallic plate [3] and is capable of absorbing all power of incident electromagnetic waves. The only source of losses in the system is the graphene sheet assuming negligible losses in the dielectric film and almost perfect reflection by the metallic plate. In a freestanding state (i.e. without the back-reflector), graphene absorbs only a small percentage of the impinging wave. However, when the impinging wave and the wave reflected by the metallic back plate come in phase at the lossy sheet, enhanced and even perfect absorption may occur. Such thin absorbers can be used as non-reflective covering layers for shielding against electromagnetic radiation and minimization of backscattering from electromagnetic large structures. Recently, an electrostatic gate-tunable perfect absorber based on a monolayer graphene over a grounded dielectric was demonstrated experimentally in the low THz regime [4]. However, an ultrafast dynamic control of the absorption properties of such devices as well as their response under simultaneous electrostatic gating remains a challenging task.

![Fig. 1.](image-url)
we use a THz time domain spectroscopy (TDS) system based on two-color filamentation of near-IR fs laser pulses in air that provides the ability of measurements in reflection mode. A part of the initial laser beam is used to excite the sample in a near-IR-pump/THz-probe configuration. The angle of incidence of the THz beam on the sample is equal to 45°, while the pump beam illuminates it at normal incidence (see Fig.1a). Our absorber consists of a simple chemical vapor deposition (CVD)-grown graphene monolayer deposited on a grounded dielectric substrate (SU-8) of thickness d = 20 μm supported by a Pt back plate (see Fig.1a).

Figure 1b shows the free carriers dynamics of the graphene layer by measuring the near-IR pump induced THz field relative reflectivity change (DR/R) as a function of pump delay. The instantaneous rise and the rapid decay equal to ~2.79 ps of the excited carriers demonstrate the fast switching capability of our device, while the negative sign of DR/R implies a negative pump-induced photoconductivity [8]. Figure 1c shows the absorption spectra of the device for variable fluence rates up to 0.690 mJ/cm² in the frequency regime from 0.75 to 8 THz. Without photoexcitation, the graphene-based structure absorbs a maximum of 75% of the incoming radiation at f = 2.17 THz. Interestingly, when photoexcited, the properties of the graphene sheet are modified and an ultrafast modulation of the absorption on the order of 40% is observed. The enhanced absorption originates from the coherent superposition of the incident and reflected wave at the absorbing graphene sheet. The decrease of the absorption in the device implies a decrease of the real part of the conductivity and points to negative dynamics.

To analyze the experimental results, we performed numerical studies of the structure’s absorbing properties, aiming at the required graphene conductivity as to reproduce the experimentally observed response. The simulations are performed in the frequency domain and graphene is simulated as a conductive sheet by imposing a boundary condition in the corresponding interface. Our numerical analysis showed that the experimentally observed response can be indeed understood and reproduced by considering reduction of the graphene conductivity by photoexcitation, connected with the generation of hot carriers, the increase of the electronic temperature, and the overall increase of the scattering rate. Figure 1d presents the results of fitting the experimental data. The experimental measurement for the case where no optical pump is applied is plotted in black. The agreement is excellent for the first resonance where the maximum modulation is recorded and remains good also for the second resonance.

The enhanced absorption can be further increased though electrostatic gating, as demonstrated in ref. [4]. Preliminary experimental results on a similar gated device reveal that apart from the increased absorption of such systems, simultaneous ultrafast laser excitation can induce also higher absorption modulation, reaching values up to 60% (Fig. 2a). More interestingly, the modulation strength depends on the applied gating voltage (Fig. 2b), indicating that even higher values can be achieved upon sample optimization.

3. Conclusions

In conclusion we investigated both experimentally and theoretically a graphene-based thin film absorber exhibiting ultrafast tunable THz operation. Our results provide evidence that in our sample, photoexcitation leads to a reduction of the THz conductivity with decay of 2.79 ps, resulting in an absorption intensity decrease of 40% at 2.17 THz. The dynamics of the photoinduced reduction of the conductivity, relate to the generation of hot carriers and the increase of the electronic temperature resulting in an overall increase of the scattering rate. Additional preliminary measurements on a gated device, reveal that photoexcitation can lead to even higher modulation strengths. Our system provides ultrathin, ultrafast modulation appropriate for the demanding future flat optics modulation applications.

References

Hyperuniform and Local Self-Uniform Solar Light Absorbers

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Abstract

We explore the ability of hyperuniform disordered structures to improve light absorption in thin-film architectures. We show that hyperuniform and local self-uniform structuring has a major impact on the radiation absorption processes and that hyperuniform and local self-uniform correlations may be designed to enhance the coupling to quasi-guided modes supported by the thin film and minimize the energy in the radiative channels. We present a thorough comparison with fully optimized periodic and quasiperiodic structures accounting for both the structuring of the anti-reflective layer refractive index and the back reflector. We show that not only the correlations of present in the disordered structures but also the statistical isotropy and homogeneity of the hyperuniform and local self-uniform materials has a significant impact on the device performance. We report a theoretical solar energy absorption of 84% in a broad band spectral range 400-1050 nm, in a one micron-thick Si membrane, which is, to the best of our knowledge, the best value achieved in ultra-thin Si membranes and preliminary experimental results.
Hybrid metal/organics in strong coupling for switchable fluorescence

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Abstract
In this paper we evidence bifunctionality properties, photochromicity and luminescence, in strongly coupled optical system. Strong coupling has been achieved between an electromagnetic mode, the surface plasmon, and two organic emitters: a J-aggregate, known for its high absorption properties and a photochromic material which absorption can be optically switched on and off. We show that the emission of the aggregated dye can be reversibly shifted between the activated and desactivated form of the photochromic material.

1. Introduction

The properties of molecules can be drastically modified when they are strongly coupled to electromagnetic modes [1,2], in particular plasmon modes [3]. The strong-coupling occurs when light-matter interaction prevails over damping and leads to a hybridization between the excitation states of matter and the plasmons. When several entities are hybridized with the same electromagnetic mode, collective effects occur which affect the system properties spectrally and spatially [4]. Different demonstrations of extended coherence have been achieved with molecules [5,6] and more recently metamaterial based on the extension of coherent states have been proposed [7]. The main interest of these metasurfaces lies in the large value of the coherence length compared to the wavelength allowing a gain of several order of magnitude in the minimal structuration size necessary to achieve the polaritonic metamaterials.

The strong light matter coupling can also be exploited to couple different molecular materials. Hybridization of remotely separated organic dyes has been performed with a microcavity [8], and efficient energy transfer has been observed between different hybridized materials [9,10]. Beside the energy transfer, the hybridization of two different materials allows a mixing of their particular properties. The advantages of organic and inorganic structures to engineer the fluorescence efficiency and relaxation processes have been theoretically demonstrated [11]. In this work we propose to mix materials with different functionalities to obtain a bifunctional system. We have chosen a photochromic material which absorption can be shifted by UV irradiation, and a luminescent material, an aggregated cyanine dye. Both are deposited on a metallic film supporting a surface plasmon. We show that the resulting system presents a switchable luminescence coupling the emitting properties of the cyanine dye and the photochromicity of the spiropyran [12].

Fig. 1 Schematic of a metamaterial sample.

2. Results

To evidence the modulation of light matter interaction, we use two organic emitters, a J-aggregate, the TDDBC, and a photochromic material, the spiropyran. The TDDBC (5,6-Dichloro-2-[[5,6-dichloro-1-ethyl-3-(4-sulfobutyl)-benzimidazol-2-ylidene]-propenyl]-1-ethyl-3-(4-sulfobutyl)-benzimidazolium hydroxide), is a cyanine J-aggregate dye from Few Chemicals. This fluorophore exhibits an intense and narrow absorption line around 2.1 eV with a FWHM of 30 meV in its aggregated form and a strong luminescence. TDDBC and more commonly J-aggregates are well-known molecules in the field of strong coupling due to their strong transition dipoles and thus their high ability to enter the strong coupling regime. The second molecule is a photochromic material (1’, 3’-dihydro-1’, 3’, 3’-trimethyl-6-nitrospiro [2H-1-benzopyran-2, 2’(2H) indole]). In its spiropyran form (SPI), it is transparent over the entire visible spectrum. After UV illumination, the molecule switches to its merocyanine form (MC) by changing its conformation and optical properties. A broad absorption band appears, spanning the visible spectrum from 1.9 to 2.5 eV.

The sample studied in this paper consists in stacked layers as illustrated figure 1. It is composed of a 50 nm continuous silver film thermally evaporated on a glass substrate. A layer
of TDBC is spin coated on the silver film, on top of which the photochromic material is spin coated in a PMMA matrix. PMMA facilitates the photochromic material deposition without any modification of its optical properties.

Based on dispersion measurements, we observe that the switching of the spiropyran into merocyanine remarkably transforms the dispersion close to resonance: the lower polariton is redshifted up to 70 meV compared to that when the photochromic molecule is in its spiropyran form. This phenomenon indicates that while activating the photochromic material, the coupling energy between the plasmon mode and the organic emitters increases revealing the tunability of the system. Figure 2: Luminescence spectra of the Ag/TDBC devices with active and non-active photochromic

Photoluminescence experiments have been carried out on the previous sample. A continuous nonresonant laser at 532 nm is focused on the top layer of the sample. Emission spectra of both TDBC-spiropyran and TDBC-merocyanine structures are shown in Figure 2. In both case, there is a peak located at 2.08 eV which corresponds to the emission of the uncoupled TDBC. When the photochromic is in its spiropyran form, the polariton emits light near 1.94 eV while the surface plasmon-TDBC-merocyanine polariton displays an emission around 1.84 eV. As a consequence, the photoisomerization induced in the photochromic layer results in a strong redshift of about 100 meV in the photoluminescence of the surface plasmon-TDBC-spiropyran polariton. The luminescence of the organic molecule mediated through the surface plasmon changes and can potentially be adjusted.

3. Conclusion

In this work, we have investigated the coupling between two different organic molecules, a J-aggregate and a photochromic, initially independent with a surface plasmon mode in a direction perpendicular to the substrate. We have presented reflectometry and luminescence measurements for different configurations where each organic emitter could be activated or deactivated. The J-aggregated TDBC presents a strong oscillator strength and a narrow and intense luminescence. The photochromic material used is reversibly switchable under UV or white light illumination. When associating these two molecules on top of a silver surface, we demonstrated that in the vicinity of the perpendicular direction of silver, the excitons can be coupled through the plasmon allowing strong and controllable luminescence. This studies open the way to bifunctional systems for which the intrinsic properties of materials could be mixed.

References

Graphene Plasmonic Oscillators for Terahertz Light Emission

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Abstract

We report the measurement of electrically-driven narrowband THz light emission from graphene. The underlying radiation mechanism involves the generation of hot carriers under current injection and their subsequent energy relaxation through the excitation of plasmonic resonances in graphene nanoribbons. Free-space THz radiation is then emitted by the resulting collective oscillations of the graphene electron gas. These results are technologically relevant for the development of highly miniaturized and broadly tunable THz radiation sources.

1. Introduction

The development of compact terahertz light emitting devices capable of room-temperature operation is a long-standing challenge in solid-state optoelectronics. These devices are desirable for many imaging, sensing, and spectroscopy applications in areas such as security screening, industrial process control, medical diagnostics, and scientific instrumentation. However, existing solutions are too bulky and expensive to allow for the widespread adoption of THz technologies in many practical settings. In looking for new materials platforms to overcome this challenge, graphene has received considerable attention due to several distinctive properties [1]. Key THz device functionalities have already been demonstrated, particularly for photodetection [2, 3] and optical modulation [4, 5]. Here, we report the first observation of electrically-driven narrowband THz light emission from graphene [6].

2. Results

The device structures employed in this work [Fig. 1(a)] consist of graphene nanoribbons connected between the source and drain contacts in a field-effect-transistor configuration. Perpendicular “bridge” sections are also introduced between neighboring ribbons, to minimize the impact of defects and cracks on the current flow through the entire device. The active material is based on commercial graphene grown by chemical vapor deposition (CVD). In this geometry, each nanoribbon act as a Fabry-Perot cavity for plasma waves. As a result, localized plasmonic modes are established at a resonance frequency $\nu_{pl}$ which depends on the ribbon width $w$ and graphene charge density $N$ according to a simple analytical expression (where $\nu_{pl}$ is proportional to $N^{1/4}/w^{1/2}$).

Figure 1: Graphene THz plasmonic oscillators. (a) Schematic device structure. (b) Measured radiation spectrum of a sample with 530-nm-wide ribbons for $V_{GS} = V_{CNP} – 75$ V, normalized to the spectrum at the charge neutrality point (CNP). The base temperature is 80 K and the input electrical power 0.2 W. Inset: top-view SEM image. The scale bar is 3 μm.

In our experiments, these plasmonic resonances are excited by an electrical current injected across the ribbons, through the generation and subsequent energy relaxation of hot carriers (i.e., carriers at an elevated temperature $T$ over the substrate). The resulting collective oscillations of the electron gas then radiate into the far field at their resonance frequency $\nu_{pl}$. Figure 1(b) shows a representative emission spectrum measured with a 530-nm ribbon-width device at a substrate temperature $T_{base}$ of 80 K, for a carrier density of about $5\times10^{12}$ cm$^{-2}$ (introduced electrostatically through the application of a back-gate voltage $V_{GS}$). This trace is normalized to the emission spectrum of the same sample gated at charge neutrality (i.e., with zero charge density), so as to fully highlight the plasmonic contribution. A sharp peak with quality factor of about 4 is observed, centered at the device plasmonic resonance frequency $\nu_{pl} \approx 8$ THz.

The measured radiation peaks also exhibit the expected geometrical and electrostatic tunability. To illustrate, Fig. 2(a) shows several emission spectra measured with another device (having 810-nm ribbon width) at different gate voltages $V_{GS}$. In Fig. 2(b), the symbols show the peak emission frequencies measured with both devices, plotted as a function of carrier density $N$. These data are in excellent agreement with numerical fits to the aforementioned analytical expression for $\nu_{pl}$ (solid lines), as well as numerical simulations based on the finite difference time domain (FDTD) method (dashed lines). The expected
increase in emission frequency with increasing carrier density and decreasing ribbon width is clearly observed, and together these devices can cover a broad spectral range of about 4 to 8 THz.

Figure 2: (a) Normalized emission peaks for \( T_{\text{base}} = 80 \) K, \( P_{\text{in}} = 0.2 \) W, and different values of carrier density (listed in the legend), for a sample of 810-nm ribbon width. (b) Symbols: peak emission frequencies measured with the two devices of Fig. 1(b) and 2(a) versus carrier density. Solid lines: numerical fits to the analytical expression for the plasmonic resonance frequency of the nanoribbons. Dashed lines: resonance frequencies computed by FDTD simulations.

3. Discussion and conclusions

In the present devices, the plasmonic emission peaks can be resolved up to a maximum \( T_{\text{base}} \) of about 190 K with nW output powers, corresponding to rather low wall-plug efficiencies on the order of a few \( 10^{-8} \). A detailed theoretical model of the underlying radiation mechanism shows that this efficiency is mostly limited by a large mismatch between the radiative and nonradiative decay rates of the nanoribbon plasmonic excitations. Significant performance improvements (including room-temperature operation) can therefore be expected by engineering the photonic environment of the nanoribbons to enhance their plasmonic radiative decay rate. The resulting devices are therefore promising towards the development of practical sources of THz radiation. Distinctive features in this respect include very small dimensions, compatibility with a wide range of substrates (including Si-based microelectronics), relatively simple and inexpensive fabrication process, broadband active tunability of the emission frequency, and the possibility of high-speed modulation.

Acknowledgements

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References

Enhancing chiral fields with arrays of achiral nanoparticles

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Abstract

Chiral light-matter interaction forms the basis for molecular circular dichroism spectroscopy, optical spin manipulation, and optical torques. Magnifying chiral effects using nanophotonics requires preserving the chiral near field. We propose the conditions and limits for enhancing chiroptical effects near achiral metasurfaces. We prove that a nanostructure cannot be universally optimal for different chiral applications. We also predict an analytical limit of maximum circular dichroism in highly evanescent Fourier orders. Our results establish guidelines for nanophotonic enhancement in diverse chiroptical applications.

1. Chirality in the evanescent near field of nanodisk arrays

Chiral light-matter interactions are a valuable optical tool with impact in biochemistry, pharmaceutics, and information technologies. Chiral interactions include diverse phenomena: circular dichroism and optical rotation by chiral molecules; [1] torques exerted on particles by circularly polarized light; [2] optical switching of magnetism in solids; [3] or the selective excitation of spins and valleys in transition metal dichalcogenides. [4] To enhance this range of phenomena, which are usually weak, a possible general approach is to exploit nanophotonic structures. Nanophotonic enhancement of chiral interactions requires, however, careful design because it combines two requirements: in addition to creating enhanced near fields, we also need to preserve chirality. Furthermore, different chiral phenomena depend on different metrics for the electromagnetic fields. As a result, the enhancement of chiral fields needs to be tailored to each application. [5]

Here, we design intrinsically achiral nanoparticles to enhance chiral light-matter interactions. [6] We compare metallic and dielectric nanodisks as representative systems where the chirality of the illumination field can be preserved in the near field. We perform numerical simulations using the surface integral equation method [7] and demonstrate strong chiral near-field enhancements. The values are further enhanced by using periodic arrays of nanodisks. We show that the enhancement behaviour is very different for different metrics of chirality – In particular, chirality metrics corresponding to distinct chiroptical interactions are incompatible with each other and cannot be enhanced simultaneously. Importantly, we derive analytically the conditions for simultaneous enhancement of various metrics of chirality, thus finding the limits of enhancement and the design considerations for different interactions. We demonstrate that silicon nanodisk arrays offer a flexible platform for enhancing different chiroptical effects. By tuning geometry and wavelength, they can provide near-field intensity enhancement optimized for either circular polarization or circular dichroism. Our results will aid the design of both single nanoantennas and metasurfaces for enhancing chiral light-matter interaction.

References


Dynamics of Nanomechanical Metamaterials: Pico-vibrometry with Light and Electron Beams

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Abstract
We report on the detection and quantitative mapping of picometre (sub-atomic) amplitude, thermal (phonon-induced) and driven movements in photonic nanostructures, using light and electron beams. These techniques enable measurements of the dynamic mechanical properties that underpin the functionality of a growing range of micro/nano-opto-mechanical (meta)materials, devices, sensors and systems, and present new opportunities in the exploration of fundamental nonequilibrium (opto)mecanics.

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Enhanced forward scattering from magnetic scatterers: design and synthesis of resonant Huygens’ sources

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Abstract

We present optical studies of nano-resonators (meta-atoms) which are designed for a specific control of their angular scattering properties in visible light. Directional scattering is obtained by adjusting the series of odd and even scattering modes. The architecture of the meta-atoms is designed to enhance the magnetic dipolar scattering which appears as the major contribution to the odd modes. Several types of meta-atoms are investigated and their scattering properties are measured. We show that the bottom-up approach enables multiple synthetic strategies and we compare their optical efficiencies.

1. Introduction

The manipulation of light by the simultaneous control of the electric and magnetic polarizability of an artificial nanostructure is a fundamental concept of the field of metamaterials. Whereas the electric response of materials to light is ubiquitous, the magnetic response is known to be negligible in natural materials. Enhancing its magnitude is a major challenge. In metamaterial composites, the magnetic response is due to inclusions (or meta-atoms) which are designed to behave like magnetic dipoles upon excitation by the light wave. Significant impacts on light control require electric and magnetic response of high and equivalent magnitude. The bottom-up approach, based on nanochemistry and self-assembly, has proven its ability to produce magnetic meta-atoms on a large-scale1,2. Four different designs have been successfully investigated in our consortium, namely plasmonic raspberries1, plasmonic dodecapods2, plasmonic nanoclusters3 and high-index dielectric particles4. Successive refinements of the designs and of the syntheses enabled a considerable increase of the magnetic and electric multipolar response. We report here on optical studies which have been developed to characterize the series of multipole scattering modes of these meta-atoms. The correlation between the modal distribution and the directional scattering is explored.

2. Optical studies

The scattering properties of the meta-atoms have been measured by a polarization-resolved static light scattering setup, as sketched in Fig.1. The scattering data are collected as a function of wavelength, scattering angle and polarization state of the input and output light.

![Figure 1: Sketch of the light scattering setup. The scattered light is collected along two orthogonal polarizations EV and EH to identify odd and even scattering modes.](image)

The analysis of the scattering signals enabled to extract the series of scattering multipoles for the different types of meta-atoms. Figure 2 shows an example obtained for spherical clusters of gold nanoparticles5. In this example, the ratio of odd (magnetic dipole MD + electric quadrupole EQ) to even (electric dipole ED) modes reaches 0.7 over a broad frequency range while the total scattering efficiency exceeds 1. The various architectures of the nano-resonators offer some degree of control on the spectral overlap of the different modes.
2. Series of scattering multipoles measured on spherical nanoclusters of gold nanoparticles of radius 7nm\(^3\). The volume fraction of gold in the nanocluster is 46%. The leading contributions arise from the electric ED and magnetic MD dipoles and the electric quadrupole EQ. The magnetic quadrupole MQ and all higher multipoles do not contribute.

3. Directional scattering

The Kerker’s condition on electric and magnetic dipoles for forward scattering has been worked out in 1983 and later extended to the full series of multipoles\(^5,6\). The full forward scattering (i.e. zero backscattering) requires a perfect cancellation of odd and even modes\(^6\). In our systems, the odd modes are MD+EQ and the even mode is ED. Figure 3 shows that the forward scattering is strongly enhanced upon approaching the generalized Kerker’s condition. Indeed, increasing the volume fraction of gold in the nanoclusters enhances the magnetic dipole and the electric quadrupole, hence producing a strong forward scattering. Moreover, the phenomena occur for a high total scattering efficiency, which may open the way to further applications in metasurfaces.

Figure 3: Polar plots in log scale of the experimental scattering from gold nanoclusters. The volume fraction of gold nanoparticles in the clusters is 27% and 46% for the red and blue symbols respectively.

4. Conclusions

New generations of resonant magnetic scatterers operating in visible light or near IR are currently produced by nanochemists along several synthetic strategies based on plasmonic or Mie resonances. The bottom-up approach enables a large-scale production at low energetic cost. The spectral overlap of the magnetic and electric resonances can be tuned by appropriate designs which enables a broadband control of the targeted optical property. Scattering efficiencies significantly larger than 1 are consistently obtained. These meta-atoms are intended for applications in self-assembled metasurfaces such as IR filters, phase retarders or broadband super-absorbers.

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References

Mimicking Magnetic Localized Surface Plasmons With High-Index Dielectrics: Enhancing Magnetic Resonance Imaging Signal-To-Noise Ratio

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Abstract

We show that surface waves supported by a negative permeability sphere (magnetic localized surface plasmons, MLSPs) can be well reproduced by the electromagnetic field scattered by a low-loss high-index dielectric sphere. In the magnetic resonance imaging (MRI) context, we suggest the use of these spoof MLSPs to enhance MRI efficiency. More precisely, we show that the MLSPs, coupled to a standard radio-frequency (RF) surface coil, are able to enhance the MRI signal-to-noise ratio with respect to standard setups. Bearing in mind that RF high-index materials are available in nature, our results suggest a simple and novel approach for the realization of magnetic meta-devices at the desired radio-frequency.

1. Introduction

Recently, we have showed that a $Re(\mu) = -1$ MM slab suitably inserted in a standard MRI setup supports resonant magnetic surface plasmons which can be exploited to enhance the MRI signal-to-noise ratio (SNR) [3]. Several nanophotonics devices are generally based on standard surface plasmon polaritons (SPPs), localized surface waves at optical frequencies excited at a dielectric-metal interface. A suitable metamaterial (MM) structure can be designed to mimic SPPs at the desired frequency [1]. These modes are known as spoof SPPs and they opened a new route for designing subwavelength photonics devices at low frequency. In addition, MM science gives us the possibility of achieving the exotic magnetic counterpart of SPPs, such as surface waves propagating along a planar surface of a negative permeability material or localized waves at a surface of a subwavelength magnetic structure, i.e. magnetic localized surface plasmons (MLSPs).

In the context of magnetic resonance imaging (MRI), a cornerstone diagnostic imaging technique, several research groups have recently proposed the use of MMs for improving MRI performance [2].

Here, we propose the use of MLSPs in the context of MRI applications. We consider a negative magnetic permeability sphere inserted in an MRI setup as displayed in Fig.1. We demonstrate that the magnetic MM sphere, coupled to a surface RF coil, is able to support MLSPs whose presence yield a strong local enhancement of the RF magnetic field. Furthermore, we prove that the electromagnetic distribution of a specific MLSP hosted by a magnetic MM sphere can be effectively reproduced by the electromagnetic fields associated to the Mie resonance of a high-index dielectric homogeneous sphere having the same radius. Considering that low-losses high-index dielectric materials are available in nature at microwave and RF range (e.g. values of $\varepsilon$ can even approach $10^4$ for some ferroelectric perovskites [4]), our results suggest the simple realization of a RF meta-device based on MLSPs, avoiding several detrimental effects arising in any MM such as high metal losses, spatial nonlocal effects and devices fabrication complexity.

2. Discussion

We consider the configuration where a surface RF coil is placed between the negative permeability sphere and the sample as shown in Fig.1. Exploiting the setup $z$-axis rotational invariance, we evaluate the electromagnetic field and the MRI SNR by using 2D full-wave simulations in cylindrical coordinates (i.e. in the $(\rho, z)$ plane) [5]. We set the frequency $\nu = 127.74$ MHz (corresponding to a static magnetic field $|\vec{B}_0| = 3$ T), $\rho_m = 8.4$ cm, $d_m = 0$ mm, $l_s = \rho_n = 3\rho_m$, $d_s = 2$ mm. In order to describe the sample electromagnetic response, we choose the dielectric parameters associated to a muscle sample ($\varepsilon_s = 63.5 + i101.2$). The RF surface coil is modeled with negligible thickness along the $z$-axis and by an azimuthal surface current distribution $J_\phi(r, z) = K_\phi(r)\delta(z)$ (\(\delta(z)\) is the Dirac delta function), where $K_\phi(r) = K_0$ for $\rho_0 - \omega/2 < \rho < \rho_0 + \omega/2$ and $K_\phi(r) = 0$ otherwise ($\rho_0 = \rho_m/2 = 4.2$ cm, $\omega = \rho_m/10 = \rho_0/5 = 8.4$ mm and $K_0$ is fixed to obtain unitary current in the coil).

At first, we focus on the case where $\rho_m = -1.20 + i0.01$ where we expect a MLSP resonance in the static limit [6]. As shown in Fig.2, we obtain a strong enhancement of both the RF received signal $|B_{1z}|/\mu_0$ and the normalized...
matching is increasingly accurate in the far-field region.

interface. The maximum deviation for deviation is tightly localized on the and a high-index dielectric sphere. We observe that the de-

viation with both a magnetic MM and a high-index dielectric sphere. In Fig.2, we compare the setups of Fig.1 with both a magnetic MM and the RF coil are in close proximity with the sphere. In Fig.2, we compare the setups of Fig.1 with both a magnetic MM and a high-index dielectric sphere. In addition, the equivalence is exact with no losses and becomes

can be evaluated by solving the complex transcendental equation

\[ \varphi_L^{(1)}(k_m \rho_m) - \mu_m \varphi_L^{(1)}(k_{eq} \rho_m) = 0, \]  

where \( \varphi_L^{(1)}(\xi) = [\xi j_L(\xi)]/[j_L(\xi)], k_m = \sqrt{\mu_m \rho_0}, k_{eq} = \sqrt{\epsilon_{eq} \rho_0}; j_L \) is the spherical Bessel function, respectively, and \( L = 1, 2, 3, \ldots \). From Eq.(1), we obtain that the configuration with the previously described negative permeability sphere is mimicked by a dielectric sphere with \( \epsilon_{eq} = 1324 + i1.65 \) (setting \( L = 5 \)). It is worth noting that the equivalence is exact with no losses and becomes more accurate in configurations without coil and sample. Of practical relevance is what happens when the sample and the RF coil are in close proximity with the sphere. In Fig.2, we compare the setups of Fig.1 with both a magnetic MM and a high-index dielectric sphere. We observe that the deviation is tightly localized on the \( z \)-axis near the air-sample interface. The maximum deviation for \( |B_{1z}^{(n)}|/\mu_0 \) is about 24\% at the point \( z = 2 \) mm and \( \rho \approx 3 \) mm, whereas the matching is increasingly accurate in the far-field region.

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References

Enhancing the second harmonic generation from nonlinear crystals by plasmonic nanostructures

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Abstract

Frequency conversion plays an important role in non-linear optics, and nonlinear crystals are frequently employed as optical elements. However, processes such as frequency doubling by second harmonic generation (SHG) still suffer from limited conversion efficiency. Here we combine commercial LiNbO3 crystals with plasmonic nanoparticles in order to boost SHG from the crystal surface. The interaction is fundamentally investigated for a single nanodisc, and maximized by a dense array of particles.

1. Introduction

Doubling the frequency of light by SHG is a vital process e.g. in laser optics. In SHG, two incoming photons are combined to create one outgoing photon of twice the energy. The conversion is enabled by interaction with e.g. crystals that exhibit an optical nonlinearity. Recently it has been shown that due to symmetry breaking, SHG can also be observed in light-matter-interaction with plasmonic nanostructures [1-3]. For applications, typically high signal intensity is sought, whereas the SHG efficiency is generally rather low. Therefore ways for improving the overall SHG enhancement are investigated. In the present work SHG enhancement is pursued by decorating commercially available nonlinear LiNbO3 crystals with plasmonic nanostructures. Depending on the cut of the crystal, the extraordinary optical axis can be chosen to be oriented in different crystal directions. In the present work, gold nanoparticles are designed to be resonant at the fundamental harmonic of the exciting pulsed femtosecond laser (774 nm laser with 110 fs pulses and a repetition rate of 89 MHz), and the crystal cut is chosen for the extraordinary axis to be oriented parallel to the respective dipolar localized plasmon polariton excitation of the nanoparticle. Two systems were investigated numerically and with linear dark-field as well as nonlinear SHG spectroscopy, see Figure 1: individual lithographically prepared gold nanodiscs on a y-cut crystal under linearly polarized excitation [4], and dense arrays of self-assembled gold nanospheres on a z-cut crystal in the focus of a radially polarized laser beam [5].

Figure 1: Schematic of the two experimental designs: SHG enhancement by (left) a single nanodisc on a y-cut crystal, and (right) self-assembled nanospheres on a z-cut crystal [6].

2. SHG enhancement by a single nanodisc

Gold nanodiscs with their diameters systematically varied around the geometry that was numerically determined to be resonant at the fundamental laser harmonic were fabricated by electron beam lithography, both on a LiNbO3 and on a glass/indium tin oxide (ITO) substrate for comparison. For both systems the single-particle dark-field scattering spectra were recorded, simulated and correlated with the particle sizes according to scanning electron micrographs. The nanodisc sizes with a near-field resonance at 774 nm were determined. Subsequently the SHG intensity in the focus of a confocal microscope was recorded for each nanodisc. For the nanodiscs on glass/ITO, all observed SHG signal resulted directly from interaction with the plasmonic nanostructures. For the nanodiscs on LiNbO3, strong SHG intensity results already from the crystal itself, and was further enhanced by the presence of the nanodisc. The electric field distribution induced in the nonlinear medium by the gold nanoparticle was calculated as well as the excitation-dependent polarization. It could be shown that the SHG from the hybrid crystal/nanodisc system surpasses the sum of the SHG measured from the pure crystal and from the nanodiscs on glass/ITO and was therefore enhanced by the crystal/nanodisc interaction. Double logarithmic plots of the power dependent SHG confirmed the second order nonlinear nature of the signal, and for LiNbO3 with a single resonant nanodisc demonstrated a 3-fold enhanced SHG intensity in the laser focus compared to the bare crystal.
3. SHG enhancement by gold nanospheres

To further maximize the SHG intensity per area, the crystal surface was covered by a dense array of quasi-hexagonally arranged gold nanospheres. These particles were prepared by block-copolymer micellar lithography, after which their size was further increased by electroless deposition of gold [7], creating plasmonic particles coupled across increasingly narrow gaps as seen in Figure 2.

Figure 2: Self-assembled gold nanospheres prepared by block-copolymer micellar lithography with subsequent electroless deposition for 200 min on nonlinear crystal.

The particle resonances were again determined by dark-field scattering spectroscopy. The SHG measurements were conducted in a parabolic mirror microscope using a radially polarized laser beam to create a strong electric field component perpendicular to the z-cut crystal surface in the focus [8]. The SHG intensity of the hybrid crystal/nanoparticle system as exemplarily seen in Figure 3 was evaluated in dependence of the particle size, and a resonant behavior was observed. With the particles closest to resonance, a >60-fold enhancement of the SHG by the hybrid system was achieved in the laser focus compared to the bare crystal.

Figure 3: SHG at 387 nm by the nonlinear crystal (blue curve) and by the crystal with gold nanospheres (red curve) under excitation with a 774 nm fs-laser, plus broad two-photon luminescence from the gold spheres at >500 nm.

4. Conclusions

In combining commercial y-cut nonlinear LiNbO$_3$ crystals with individual gold nanodiscs, and z-cut crystals with dense arrays of self-assembled gold nanospheres, it is shown that the near-surface SHG from the crystals can be strongly enhanced by the nanoparticles’ near-fields that extend into the crystals. In the laser focus of a confocal microscope, a 3-fold enhancement of the near-surface SHG was observed for a single nanodisc, which was amplified to a factor of 60 for the particle array, making the arrangement attractive for nonlinear sensing experiments.

Acknowledgements

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References

Polarisation study of the light scattered by nanoporous plasmonic microparticles

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Abstract
Nanoporous microparticles exhibit large surface-to-volume ratio and can detect chemicals and biomolecules. Using dark-field microscopy, we observed that, when the nanoporous microparticles are illuminated by circularly polarized laser beams, the scattered light polarization is inverted. The inversion is interesting as the microparticles are (nearly-)spherical, and the nanopores do not exhibit symmetry. We observed that the scattered light polarization is tunable when plasmonic Ag nanoparticles and short molecules are in the pores. We discuss these findings and their exploitation as sensors.

1. Introduction
The excitation and radiation of plasmonic structures and nanostructures are well-known to depend on their shape and geometry, and on the polarization of the light that excites or that is detected. Plasmon-mediated fluorescence in Au nanorod [1] and photoluminescence in single Au nanowire [2] exhibit a strong dependence on polarization. Polarization is one of the key attributes of light and controlling the state of polarization leads to a variety of scientific findings and a plethora of applications [3]. Chiral metamaterials of have been designed to control or switch the polarization states of light, for example by switching the linearly polarized light from one polarization to its crossed polarization [4, 5]. Changes in the polarization state of light in plasmon-based materials are also used in a variety of molecular sensing platforms, with the well-known surface plasmon resonance (SPR) method using a scheme derived from ellipsometry to assess a change in refractive index at the sensor surface, then associated to the adsorption of the targeted molecular species or biomolecules. Porous silica and silicon stand apart thanks to their morphological structure, which includes large surface to volume ratio, adjustable porosity and pore sizes, along with low-cost fabrication and compatibility with microfabrication technologies. Using microparticles that can mix and freely circulate in liquid increases the likelihood of detection, and mobile microparticle sensors are thus especially suited in a variety of sensing schemes. Here, we have embedded Ag nanoparticles in nanoporous silica microspheres and studied the polarization of the scattered light using a dark field microscope. We observed that when the incident light is circularly polarized, the scattered light polarization is inverted for wavelengths around the plasmon resonance. Remarkably, the inversion is not seen when monolayers of dodecanethiol (DDT) or of ethynylaniline (EA) are added into the silvered pores, making the method highly sensitive if developed as a sensing platform. We also discuss how the polarization phase relates to the observations and can be proposed to justify these new findings.

2. Methods and Results
Nanoporous silica microparticles (1.5 μm) were measured after thorough cleaning and after reduction of silver salt at the surface and in the nanopores [6]. Darkfield spectra were recorded using a home-made microscope based on a high NA oil immersion DF condenser (NA 1.2-1.3), a broadband white light source, a collection objective (NA 0.9), and an ACTON spectrograph. A redshift of the wavelength of the maximum scattering is measured when DDT and EA are added (Figure 1).

For polarization studies, we built a second transmission microscope using a low NA (<0.6) objective to focus a visible monochromatic tunable laser beam onto the microparticles deposited on a glass slide and attached to a piezo scanner to record images. The collection was made by a darkfield objective (NA 0.8, with the low NA core blocked) and the scattered light was measured with a photomultiplier (PMT). A tunable quarterwave plate (QWP) was used to achieve on the sample circular polarization of the originally linear polarized incident beam, and a second
QWP was introduced in the detection path so that the circular polarization is made linear again for analysis with a linear polarizer (LP) in front of the PMT. The polarization and second QWP alignment were verified in bright field before darkfield measurements.

In Figure 2, we show that in bright field the circular polarization (red) remains unchanged and other data shows that this is the case for any wavelength and systems tested, as expected since most of the incident light is transmitted with little perturbation. Our main finding is that the scattered light measured in darkfield (blue) has a polarization that strongly depends on the wavelength and on the Ag surface (ie, with or without the addition of EA and DDT). We found this inversion of the polarization remarkable given that the system is spherical and its porosity is amorphous. We discuss theoretical evidence, based on COMSOL Multiphysics, that the changes in polarisation are likely due to variations in the polarisation phase in the specimen and on the porous nature of the microspheres.

3. Conclusions

As an important property of plasmonic material, the polarization of the scattered light in nanoporous SiO$_2$ microspheres coated with Ag nanoparticles was investigated by darkfield micro-spectroscopy. Illuminating the microparticles with circularly polarized lasers lead to an inversion of polarization that is further tuned by the addition of a monolayer of DDT or EA. We propose that these particles and polarization scheme can be used for sensitive sensing of molecule adsorption at single particle level.

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References

Measurement of the quantum geometric tensor and of the anomalous Hall drift in a continuous medium

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Abstract

We report a direct measurement of the Berry curvature and of the quantum metric in a 2D continuous photonic medium. The measured components of the quantum geometric tensor are used for a quantitative prediction of the anomalous Hall effect, which is then confirmed by experiment.

1. Introduction

Topological photonics is a field of intense research. The non-trivial topology of the bands is characterized by their Berry curvature, computed from the wavefunctions of the eigenstates at different wave vectors:

\[ B = i \nabla \times |\psi\rangle \langle \psi| \] (1)

The integral of the Berry curvature over a closed manifold is the Chern number. A non-zero Chern number means a non-trivial topology associated with chiral edge states at the boundary with a topologically trivial surrounding. However, a non-zero Berry curvature can lead to interesting effects even when such edge states are absent (for example, when there is no boundary). Among these, one of the most well-known is the anomalous Hall effect [1], in which a transverse drift can appear even for neutral particles.

It is less well-known that the Berry curvature is a component of a more general object: the quantum geometric tensor, defined as

\[ T_{ij} = \left\langle \frac{\partial \psi}{\partial q_i} | \frac{\partial \psi}{\partial q_j} \right\rangle - \left\langle \frac{\partial \psi}{\partial q_j} | \frac{\partial \psi}{\partial q_i} \right\rangle \] (2)

where \( q_{i,j} \) are the variables of the parameter space, for example, the projections of the wave vector. Berry curvature is the imaginary off-diagonal part of this tensor, while its real part is the quantum metric.

While the Berry curvature characterizes the "twisted" behavior of the eigenstates, the quantum metric allows to measure the distances between the neighboring states, independently of their "twist": it can be present even when the Berry curvature is zero. The quantum metric, linked with the concept of fidelity, well-known in the field of quantum informatics, is important in all dynamical experiments: it determines the non-adiabaticity of the excitation and the evolution of the wave function.

So far, Berry curvature has only been measured by indirect methods [2], while the studies of the quantum metric were even more scarce [3]. The photonic systems offer a particular advantage: the access to the direct measurements of the eigenstates, from which the quantum geometry can be extracted. This extraction is the subject of the first part of the present work [4].

The quantitative extraction of the quantum geometry allows to make quantitative predictions concerning the dynamics of wavepackets in the non-trivial photonic bands. We calculate the anomalous Hall effect using the measured band geometry and then confirm the theoretical predictions by experimental measurements of this effect.

2. Measurement of the quantum geometric tensor

We study a high quality planar microcavity with embedded quantum wells in the regime of strong coupling. The polariton modes exhibit a spin-orbit coupling stemming from the TE-TM splitting. They are also sensitive to magnetic fields via the Zeeman splitting of the excitonic fraction. The Hamiltonian of the two polarizations of the lower polariton branch accounting for these effects reads:

\[ H_k = \left( \frac{\hbar^2 k^2}{2m^*} + \Delta_x, \frac{\alpha - \beta k^2 e^{-2i\phi}}{2m^*} - \Delta_z \right) \] (3)

where \( m^* = m_1 m_2 / (m_1 + m_2) \), with \( m_1 \) and \( m_2 \) being the longitudinal and transverse effective masses. \( k = |k| = \sqrt{k_H^2 + k_V^2} \) is the in-plane wavevector (\( k_H = k \cos \phi \), \( k_V = k \sin \phi \), \( \phi \) is the propagation angle). \( \Delta_x \) is the polariton Zeeman splitting. \( \alpha \) is the optical birefringence, leading to a \( k \)-independent splitting between horizontally and vertically (HV) polarised states. \( \beta \) quantifies the \( k \)-dependent TE-TM splitting. This \( 2 \times 2 \) Hamiltonian can be decomposed in Pauli matrices, describing the interac-
where $r$ is the wavepacket center of mass, $E(k)$ is the dispersion, $F(k)$ is the accelerating force, $B = B_2 \hat{e}_2$. The acceleration is provided by the thickness gradient of the microcavity.

The measured centre-of-mass trajectories, which will be shown in the talk, are well reproduced by numerical simulations based on the semiclassical equation (6), using as input parameters the potential and the Berry curvature distribution computed using (3),(5) and the experimentally fitted parameters.

4. Conclusions

Our experiments provide a measure of both the full non-trivial band geometry of a 2D continuous system and, independently, real space wavepacket motion demonstrating anomalous Hall effect and non-adiabaticity. It supports the validity of the semiclassical approach and band geometry to compute wavepacket dynamics, opening the way for quantitative optovalleytronics. Our results demonstrate that 2D photonic modes, because they are TE and TM polarised, carry topological charges, essential for topological photonics.

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References

Monochromatic THz radiation of relativistic electrons from a metasurface

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Abstract

We report on experimental and theoretical studies of coherent THz Smith-Purcell radiation and grating transition radiation generated by an electron bunch from a metasurface. The results are compared, and agreement is found to be marvelous for spectra, while angular distributions show discrepancy. We show that, qualitatively, the difference in angular distributions can be caused by contribution of such processes as coupling between particles or excitation of surface plasmon-polaritons.

1. Introduction

Research of coherent radiation using electron beams is the growing area aiming at the development of radiation sources and beam diagnostics. While transition radiation (TR) is the more strong mechanism, most interest excites Smith-Purcell radiation (SPR), for which an electron beam passes above a grating. This scheme is not only non-invasive for both target and the beam, but also lets involving all the elements of the surface structure in the radiation process. Yet, TR is of significant interest in practice, especially in case of grating-like target, when TR spectrum is quasi-monochromatic (predicted in [1] and first experiment in [2]) similar to that of SPR.

Nowadays, new types of target are investigated, including photonic [3] and plasmonic crystals [4], metasurfaces [5] etc. What is challenging in investigating that is an attempt to find the way for effective control of radiation properties, particularly in THz range. While there are a lot of computer simulations [6], the experiments are not so often [7], and theory is practically undeveloped.

In this report we show first experimental and theoretical results on generating grating TR (GTR) [2] and SPR from a metasurface made of subwavelength elements arranged on the surface of dielectric substrate, see Figure 1a.

2. Experiment

The experiment was carried out at LUCX facility in KEK, Japan [8]. The pC electron beam was produced by illuminating a Cs2Te photocathode by 3rd harmonic Ti:Sa laser beam (266 nm) with femtosecond pulse duration and 3.13 Hz repetition rate. Single bunches were accelerated to 8 MeV in a 3.6 cell S-band RF gun. The layout of the experiment is shown in Fig. 1b. The target is truncated copper cones of 300±2 μm in bottom diameter, and 150±1 μm in top one, forming an array with periods 1480 μm and 330 μm. The substrate is made of monocrystalline sapphire of 500 μm thick.

3. Theory

The distribution of radiation over the solid angle dΩ and photon energy dℏω is defined by the field of radiation

\[ E^{rad}(r, \omega) \] for arbitrary angle of incidence of the electron on the target θ. Size \( R_b \) of metal particles is much smaller than the wavelength of radiation \( λ \), so we can use the approach developed in [2,9], and obtain the field of radiation generated by a single electron in the wave-zone:

\[
E^{rad}(r, \omega) = \alpha(\omega) \frac{i e^{i\omega}}{\pi v} \frac{e^{i\hat{a} r}}{r} e^{i(k(p \sin \theta - z_a \cos \theta) + i \omega \tau_a/\gamma)} \times \\
\sum_{m_z} \sum_{m_y} \sum_{m_x} (k(R) - k^2 R)e^{-im_zm_y}e^{im_x(p \cos \theta + i \sin \theta)}.
\]

(1)

Here \( e \) is the charge of electron, \( \omega \) is the radiation frequency, \( k = n \omega/c \) is the radiation wave-vector with \( n \) being the unit wave-vector, the array is supposed to consist of \( N = 2N_z(N_l + 1) \) particles, with \( N_{l,z} \) being the number of monocrystalline sapphire of 500 μm thick.
of particles, \(d_{1,2}\) are the periods of the array, \(m_{1,2}\) are the integers counting the particles in corresponding directions, \(\alpha(\omega)\) is the polarizability of the particles, \(h\) is the impact-parameter, \(\varphi = \omega n^{-1} - k_z\), \(e_{x,y,z}\) being the basisvectors,
\[
R = \frac{\alpha e}{c\beta^2} K_0 \left( \frac{\omega}{\nu y} t \right) + i \frac{\omega}{\nu y} t K_1 \left( \frac{\omega}{\nu y} t \right),
\]
\[
t = d_2 (m_2 + 1/2) e_y - (d_1 m_1 \sin \theta - h \cos \theta) e_x.
\]
For \(\theta = 0\) the emitted radiation is referred as SPR, otherwise it is referred as GTR. The maximal intensity of GTR would arise at parameters defined by dispersion relation:
\[
\lambda s = d_1 \left( (\beta^2 - n_1) \cos \theta + n_1 \sin \theta \right), \quad s = 0, \pm 1, \ldots
\]
Formulae do not include radiation from a substrate (TR or Cherenkov radiation) as they do not interfere with SPR or GTR, because they are emitted at different angles.

4. Discussion

The experimental orientation dependences of GTR shows maximal signal at \(\theta = 22.7\) degree and additional maxima at 25 and 20 degrees that are not predicted by the theory. Among reasons there can be the anisotropic properties of a window of vacuum chamber, anisotropy of a substrate, refraction of the radiation, or other repeatable processes. Spectral dependences were measured at \(\theta = 22.7\) degree. Both frequency of emitted radiation and spectral width coincide with the theoretical ones, see Figure 3a.

![Figure 3: Experimental and theoretical reconstructed spectrum of (a) GTR, (b) SPR.](image)

According to orientation dependence monochromatic SPR generates at \(\theta = 0.5\) degree. Such a shift from zero-angle as well as slight shift in spectrum at \(\theta = 0.5\) degree (see Figure 3b), can be explained by deviation in grating period from declared. On the other hand, the narrowness of the spectral line proves that measured signal originates from a grating. Also, the deviation of measured curves from theoretically predicted can be explained by unaccounted interaction between grating elements. This problem was considered for of two coupled particles in [10]. As the substrate was dielectric while the grating was metal, we do not exclude the appearance of plasmon resonances as well. However, special conditions are needed to observe them. Besides, the presence of resonance peaks is very sensitive to the combination of grating and beam parameters, so the study of such resonances is a separate problem.

5. Conclusions

In summary, we investigated both theoretically and experimentally the monochromatic radiation generated by relativistic electrons. The target – metasurface consisting of arranged sub-wavelength metal particles on the dielectric substrate – emits Smith-Purcell radiation, and, for other incident angles, grating transition radiation in THz range. The constructed theory correctly describes the radiation spectra, while angular dependences show discrepancy, which can be evidence of the contribution from other radiation mechanisms, like surface plasmon-polaritons, or effects of coupling between the elements of the metasurface.

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References

On-chip guiding of spoof terahertz surface plasmon polaritons on metasurface pathways

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Abstract

We investigate the guiding and routing of spoof terahertz surface plasmon polaritons (terahertz SSPPs) along metasurface pathways of subwavelength width by means of numerical calculations and experimental measurement of the spatio-temporal and spectro-temporal dynamics of the electric field of the SSPPs. The pathways are composed of single-, two- or three-cut wires. The metasurfaces are designed to sustain terahertz SSPPs with both a strong out-of-plane and in-plane confinement. The SSPPs are routed along straight and curved pathways of subwavelength path width. We study the impact of the path width on the out-of-plane confinement of the SSPPs and on their spatio-temporal and spectro-temporal properties. We show that terahertz SSPPs can be tightly guided within subwavelength space on metasurfaces without loss of the out-of-plane confinement, which renders metasurfaces suitable for guiding terahertz SSPPs on a chip level.

1. Introduction

Integrated circuits revolutionized electronics decades ago and have been an integral part in literally all electronic circuits ever since. Following the promising example of electronic integration, scientists applied integration technology in photonics to implement fully-functional optical devices in tiny space. In such photonic circuits, electromagnetic waves usually interact with the electrons in metal micro- or nanostrips and build a new quantum-mechanical quasi-particle, which is called a surface plasmon polariton (SPPs). SPPs can be tightly confined to the metal surface, provided the dispersion of the metal in the considered frequency range of the SPP is strong enough. However, due to the Kramers-Kronig relation, strong dispersion also causes a strong propagation damping of the SPPs, which implies that SPPs with strong surface confinement can only be used to transport information and energy over small distances along the surface. In the terahertz frequency regime, the dispersion of SPPs on flat metal surfaces is very weak and SPPs cannot closely bind to the surface. As shown in [1,2], the surface confinement of SPPs can be artificially increased, when the metal surface is corrugated. The observed, so-called spoof SPPs (SSPPs) properly mimic the properties of SPPs on flat metal surfaces. Even in a more flexible way, SSPPs can also propagate along metasurfaces [3]. As a great advantage, metasurfaces can be deliberately designed to manipulate the spatio-temporal and spectro-temporal properties of SSPPs at will [4]. In integrated circuits, it is especially important that the SSPPs are not only confined in the direction perpendicular to the surface, but also are tightly guided on pathways with path widths of the order of one wavelength. Yet to date, the effect of lateral confinement of SSPPs on the spatio-temporal and spectro-temporal properties of terahertz SSPPs has been only sparsely studied. In particular, current research lacks experimental investigation and verification [5-7].

Here, we theoretically and experimentally examine terahertz SSPPs on metasurface pathways of subwavelength path width. We show that such metasurface pathways can tightly guide SSPPs along straight and curved routes without sacrificing the out-of-plane confinement of the SSPPs. We carefully investigate the impact of the path width on the spatio-temporal and spectro-temporal properties of the SSPP modes by numerical simulations and by measuring the electric near-field of the SSPPs with a terahertz time-domain near-field microscope.

2. Discussion

Figure 1 shows an example of propagating terahertz SSPPs on a curved metasurface pathway. As can be seen in the microscope picture of the fabricated metasurface in Fig. 1(a), the metasurface pathway is composed of 3-cut-wire unit cells. The numerically calculated distribution of the z-component of the electric field at a frequency of 0.3 THz indicates that the SSPP field is tightly guided within the boundaries of the curved pathway with a strong field enhancement at the path margins. These findings are verified by the measurement of the electric near-field distribution of the SSPPs at a distance of 50 \( \mu \)m away from the metasurface. By use of the terahertz near-field microscope, both the amplitude and phase of the electric SSPP near-field was measured, thus providing the full spatio-temporal and spectro-temporal dynamics of the SSPPs. The measured electric SSPP near-field distribution is in good agreement with the numerically calculated results and confirms a strong confinement of the terahertz SSPPs within the boundaries of the curved pathway.
3. Conclusions

We theoretically and experimentally studied the propagation of terahertz spoof surface plasmon polaritons (terahertz SSPPs) on metasurface pathways of subwavelength width. We showed that terahertz SSPPs can be tightly guided on a curved pathway without sacrificing the out-of-plane confinement. The numerically calculated electric SSPP field and the measured electric SSPP near-field are in good agreement and confirm the out-of-plane and in-plane guiding properties of the metasurface pathways.

Acknowledgements

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References


All dielectric 3D periodic nanoresonators for phase and polarization control of SH light.

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Abstract

We demonstrate numerically and experimentally enhanced efficiency and polarization control of nonlinear mixing via 3D all-dielectric periodic nanostructures. The 3D spatial periodicity allows diffractive interferences of SH light for the phase control, while the meta-atom geometry allows the excitation of Mie-modes for polarization control.

1. Introduction

Nonlinear periodic structures, that is to say two or three-dimensional periodic arrangements of high and low refractive index materials have been proved essential for efficient and tailorable nonlinear mixing [1-3]. Plasmonic metamaterials for instance, where \( \lambda/n >> \lambda_{Mie}/n \), have shown efficient nonlinear mixing via effective tuning of the unit cell parameters [1]. All dielectric 2D and 3D photonic crystals (PC), instead, where \( \lambda/\eta_{eff} > \lambda_{Bragg}/\eta_{eff} = 2p \), have reported nonlinear mixing enhancement, based on either phase matching conditions near the PC band gap [2], or surface high field localization when pumping at the bandgap wavelength [3].

Besides periodic structures, when the incoming light is also coupled to displacement currents of the constituent meta-atoms, where \( \lambda/n = \lambda_{Mie}/n = \lambda \), with \( \lambda \) the incident FW, and \( n \) and \( L \) the meta-atom refractive index and characteristic size, respectively, the nonlinear wavefront can be further shaped depending on Mie-scattering of the individual nanoresonators.

We have recently demonstrated the independent control of phase and polarization states of SHG from monolayer all-dielectric metasurfaces [4-5]. In those works in-plane spatial periodicity allowed zero-order diffractive interferences of SH light for the control of SH phase, while the meta-atom geometry allowed the excitation of Mie-modes which ensure the control of SH polarization.

2. Results and discussions

In this work we extend SHG phase and polarization control to a 3D PC made of a stucco of three metasurfaces (see figure 1a). The spatial periodicity extended to the third dimension allows even further enhancement of the SH amplitude in the zero order diffraction, while the SH polarization can be independently controlled via the meta-atom geometry. Figure 1b reports a map of the SH near field with high field confinement in correspondence of the mode excited at the SH frequency. Our simulations predicts a 100-fold enhancement of SH efficiency with respect to the metasurface, while in the experiments we have measured a 20-fold enhancement. A SEM figure of the sample is reported in Figure 1c.

Figure 1: a) Schematic of the 3D photonic crystal. b) SH near field map c) SEM image where red and blue shadows are as in a)
3. Conclusions

We show that extending the PC optical regime to the third dimension improves the SH phase control with a measured SH enhancement of 20 times with respect to a monolayer metasurface. By also achieving an independent control of polarization via the metaatom geometry, this work paves the way for applications like free-space optical interconnects.

References


Plasmonic Probe for Electrochemical Reaction at Metal Nanostructures

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Abstract

Light-matter interaction is normally defined by the response of electronic structures of materials under the polarization by photons at long wavelength approximation. This approximation, however, should be modified, if the size, speed, and apparent mass of photons are different from those of normal light. Plasmon can be used as energy quantum to excite electronic structures of materials. Recent studies prove that plasmon-excitation shows distinct characteristics at electronic excitations. We have proposed that spectroelectrochemistry is powerful tool to investigate electronic sates and geometrical structures of electrified interfaces in-situ under the conditions where photonic and electronic energy conversion functionalities emerge. One can use plasmon-powered processes to expand the ability of the spectroscopy regarding sensitivities in space, time, and energy resolutions. As their characteristics on localization of surface plasmons into molecule scale, huge intensity gradient of electromagnetic field would break the limit of light-matter interactions via the modification of the selection rule of the electronic excitation process. Surface-enhanced-Raman scattering (SERS) is the probe to monitor the exotic electronic excitation processes.

In this talk, we will show that single layer graphene can used as to determine the electronic structures of plasmonic nano-electrodes for photoelectrochemical energy conversions. Using the electrochemical Raman measurements of the graphene layer under the near-infrared light illumination, we have revealed the relationship between the photoenergy conversion ability and electrochemical potential of the Fermi level of the plasmonic structure. The measurements are based on in-situ monitoring G and 2D Raman bands of graphene layer on plasmonic structures. The present electrochemical Raman measurements was proved to provide detailed understanding on the plasmon-induced charge transfer process for further developments on the ability.

References

Nanophotonics and femtosecond magnetism in all-dielectric metasurfaces

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Abstract

Light manipulation in magnetic nanostructured materials attracts much attention in the context of data processing, spintronic and light modulation applications. In this work we demonstrate a subwavelength light localization within the magnetic dielectric metasurface made of bismuth-substituted iron garnet leading to light intensity modulation and an efficient magnon excitation. The advanced light control and selective spin manipulation are achieved due to appearance of various types of excited modes in the nanostructured surfaces.

1. Introduction

Optical manipulation by magnetic field is used in various areas including non-reciprocal devices, isolators, sensors, etc. At the same time a non-thermal magnon excitation at ultrashort time scales by light pulses is of prime interest in context of the data processing and spintronic applications. Femtosecond laser excitation of bismuth-substituted iron garnet is implemented as an efficient and flexible way to excite spin waves in terms of spatial location of a spin wave source, types of spin waves \cite{1,2}, directional emission pattern \cite{3}, and wavelength \cite{4}. All-dielectric films of bismuth-substituted iron garnet are optically transparent media with high magneto-optical response and are promising for many applications. However, subwavelength spatial light localization that can be utilized for devices miniaturization or nanosized spin waves emitters is still lacking. In this work, we investigate magneto-optical effects in nanostructured bismuth-substituted iron garnet gratings and demonstrate the new ways to control light together with enhancement of excitation efficiencies of different types of spin waves.

2. Experimental

The all-dielectric iron garnet gratings that provide a metasurface have been formed on the films of Bi\textsubscript{0.7}Gd\textsubscript{0.3}Lu\textsubscript{2}Ga\textsubscript{0.3}Fe\textsubscript{4.7}O\textsubscript{12} (BiIG) epitaxially grown on a gadolinium gallium garnet (GGG) substrate by ion etching. Substitution of rear-earth ions with bismuth significantly enhances the magneto-optical response in these films. The typical width of 1D trenches and diameter of 2D nanopillars was 250 nm and 200 nm, respectively. The height of structures was 225 nm and the underneath BiIG film was 75 nm thick, while the period for both types of structures was 400 - 450 nm. A scanning electron microscope images of the formed structures are presented in Figure 1.

In order to investigate the excitation of magnetization precession, we used the pump-probe experimental technique. The laser system (Newport Mai Tai HP Ti:Sapphire laser and Spectra-Physics Inspire Auto 100 optical parametric oscillator) emits at 80.54 MHz repetition rate pairs of 150 fs-pulses that are tunable in wavelength. The probe pulse is used for observation of the magnetization dynamics through the direct Faraday effect, i.e. by measuring variation of the Faraday rotation angle, Ψ, caused by the magnetization precession. Pump wavelength was set between 800 to 900 nm, while the probing was performed at the double frequency. The average pump light energy fluence was set to 0.6 mJ/cm\textsuperscript{2}.

3. Discussion

The studied BiIG structures support quasi-waveguide mode excitations which propagate along the structures and scatter on the nanopillars or trenches. The patterned surfaces are used to provide coupling between the incident light and the quasi-waveguide modes via the diffraction on the periodic lattice. Figure 2 (top panel) demonstrates the transmittance spectra counter plot for various excitation wavelengths and light incidence angles. The regions with the resonant light absorption, in the form of spectrally narrow dark color lines (Fig. 2 top panel), indicate the excitation of quasi-waveguide modes in the structure. Existence of the discovered new modes provides enhancement of magneto-optical effects \cite{5}.
Further we perform the pump-probe measurements in order to investigate the magnetization dynamics behavior of the nanopatterned structures when the femto-second light excitation is matching the quasi-waveguide modes region.

Figure 1: a) scanning electron microscopy image of BiIG 1D nanostructure. b) 2D nanopatterned BiIG film.

Figure 2: Top: optical transmittance spectrum of the 2D BiIG grating depending on the light incidence angle, when excited with circular polarized light. Bottom: transient Faraday rotation for solid film (blue color) and 2D grating (red color). Pump excitation with circular polarized light at a wavelength matching the region of existence of a quasi-waveguide mode (in a 2D grating).

Figure 2 bottom image demonstrates the transients of the Faraday rotation in a metasurface of 2D nanopillars (red color) and a smooth BiIG film (red color). Femto-second light pulses launch the magnetization precession in both types of samples. In the case of a smooth film the signal can be fitted with a decaying sine function, demonstrating the magnetization precession with one frequency. While for the case of the nanopatterned sample we detect the beating behavior, that indicates an additional frequency component. Moreover, the amplitude of the Faraday rotation gets enhanced for the metasurface sample. Nanopatterning of a magnetic film leads to a nonuniform distribution of the inner magnetic field allowing appearance of different types of spin waves upon excitation. For the case of the 1D trenches on the surface of the BiIG film optical pulses launch magnetostatic and exchange spin waves of the first and second orders. Amplitude intensity of the excited exchange spin waves can be modified by the polarization variation of the pump beam, which provides new way of tunability for magnons excitation.

4. Conclusions

In this work we study the new effects that emerge as the result of a nanopatterning of all-dielectric films of bismuth-substituted iron garnet. We detect the quasi-guided modes that are sensitive to the magnetization of the structure providing an approach for light propagation control and result in appearance of new magnetooptical intensity effect. When short laser pulses are used to excite the BiIG metasurface, the generation of exchange spin waves becomes feasible. For smooth films launching of exchange spin waves is generally not possible, and only magnetostatic ones are present. Spin waves amplitude intensity can be controlled by the light polarization, while the frequencies are governed by the nanopatterning. Ultrafast optical non-thermal excitation of various types of spin waves provides a new route for the spin manipulation for applications.

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References

New Plasmonic System for Visible Light-Driven Hydrogen Evolution Reaction

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Abstract
Excitation of the localized surface plasmon resonance leads to the generation of the reaction active species. The excited species makes it possible to trigger the efficient multi electron transfer reactions. In this study, plasmon-induced hydrogen evolution reactions have been achieved by the introduction of the the plasmonic metal nanostructures intto the p-type GaP semiconductor electrode. Through the photoelectrochemical measurements, the unique molecular process has been confirmed at the present plasmonic photocconversion electrode, resulting in the unique reaction selectivity.

1. Introduction
The efficient use of the light energy is key process for the sustainable society. One of the way for it can be considered as the usage of the localized surface plasmon resonance (LSPR). With the excitation of LSPR by the visible light illumination onto the plasmonic metal nano-structures, it is possible to confine the light energy at the nano scale region. At the plasmonic field, various unique photo chemical phenomena can be observed, such as the light-matter interaction, the selection rule break down in the electronic excitation, or photochemical reactions. [1] Regarding to the plasmon-induced chemical reactions, it is known that the combination of the wide bandgap semiconductor electrode with the plasmonic metal nanostructures realizes the visible light induced chemical reactions. In this system, the barrier of the wide bandgap electrode which the photoresponse ability of it is limited to the ultraviolet region can be overcome due to the addition of the visible light response character of plasmonic materials. Generally, the representative plasmonic photocconversion system consists of the combination of the n-type semiconductor electrode with the plasmonic metal nanostructures. Under the visible light illumination, the electrons are excited within the metal structures and, then, injected into the conduction band of the n-type semiconductor. At that time the remained holes are consumed through the oxidation reaction at the metal-semiconductor interface. In our previous study, we have succeeded in not only the visualization of the reaction active sites but also the determination of the absolute electrochemical potential of the reaction active species by using the polymerization of the conductive polymer [2]. Although well-established systems have been reported, the direct control of the reduction reaction at the metal-semiconductor interface by the excited electrons has not been well examined.

On the other hand, among the various type of electrochemical reactions, hydrogen evolution reactions are one of the important and well-studied reactions because of its importance. Up to date, a lot of works have been carried out for the examination of the catalytic performance, the kinetic constants, and so on. In our previous work, we have revealed that the molecular process at the nanostructured metal electrode drastically changed, leading to the unique isotopic selectivity [3]. From above backgrounds, at the present study, we have attempted to fabricate the visible light-induced hydrogen evolution system by the introduction of the plasmonic structure into the surface of the p-type semiconductor electrode. In this system, it would be expected that the unique surface molecular process which is different from that in the absence of the plasmonic field.

2. Experiment
Single crystal p-type gallium phosphide ((111), Zn-doped: 4.8 × 1018 cm−3) (p-GaP) was used as the semiconductor electrode. Plasmonic nanostructures were prepared by the nano-sphere lithography method which used the polystyrene beads with the diameter of 350 nm as the template [4]. The photocurrent measurements have been performed by using the three electrode cell (left part of Fig. 1a). The plasmonic p-GaP electrode, Pt plate, and Ag/AgCl electrode were used as the working, counter, and reference electrodes, respectively. The plasmonic p-GaP electrode was contacted to a stainless plate with an In-Ga ohmic contact. The illuminated light wavelength is 650-900 nm.

3. Results and Discussion
As the plasmonic structure, well-defined Au structures were fabricated on the entirely surface of p-GaP as shown in the right part of Fig. a. Photocurrent measurements have been performed using p-GaP and plasmonic structure supported p-GaP electrodes. In the case for p-GaP electrode, no-photocurrents were observed under the visible light
illumination. This is due to the wide band gap energy of p-GaP ($E_g = 2.26$ eV ($\lambda = 550$ nm)). On the contrary, the plasmonic photoconversion electrode shows the photocurrent generation the visible light illumination. This result indicates that the hydrogen evolution reaction is triggered by the excited electrons while the generated holes were injected into the valence band of the p-GaP. From this result, it can be said that the current visible light driven hydrogen evolution system has been achieved.

As the next step, we have examined the pH dependence on the photoconversion property. The left and right photocurrents shown in Fig. 1b were the results obtained under acid and neutral condition, respectively. Basically, the hydrogen evolution reaction under the acidic condition shows higher efficiency compared to neutral or basic condition because the hydrogen evolution is the proton-coupled process. Despite this basic electrochemical character, the obtained photocurrent values for neutral condition was comparable to that for acidic condition. This could be originated from the change in the surface molecular process caused by the effect of the optical field under the neutral condition. Based on this fact, we have examined the isotopic effect which provides information about the surface molecular process. Through this investigation, we have revealed the change in the surface molecular process at the plasmonic nanostructure surface. At the present, the origin for the unique isotopic selectivity can be considered as the contribution of the modification of the electronic excitation at the plasmonic field.

4. Conclusions

In conclusion, we have successfully established new plasmonic system which makes it possible to trigger the visible light driven hydrogen evolution reaction. It is interesting that the appearance of very unique modification of the surface molecular process has confirmed through the examination of pH dependence and isotopic effect. From present investigations, it can be said that our present photoconversion system would have the possibility for the new

References


Fig. (a) Schematic illustration of the three electrode cell and AFM image of plasmonic nanostructures deposited on p-GaP. (b) Photocurrent measurements of plasmonic p-GaP electrode under visible ($\lambda > 600$ nm). The solution conditions for (left) and (right) were acid and neutral, respectively. The electrode potential was set to −0.3 V.
Biomimetic Ultra-Broadband Perfect Absorbers Optimised with Reinforcement Learning

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Abstract
By learning the optimal policy with a double deep Q-learning network (DDQN), we design ultra-broadband, biomimetic, perfect absorbers with various materials, based on the structure of a moth’s eye. All absorbers achieve over 90% average absorption from 400 to 1,600 nm. By training a DDQN with moth-eye structures made up of chromium, we transfer the learned knowledge to other, similar materials to quickly and efficiently find the optimal parameters from the ~1 billion possible options. The knowledge learned from previous optimisations helps the network to find the best solution for a new material in fewer steps, dramatically increasing the efficiency of finding the best designs for ultra-broadband absorption.

1. Introduction
Antireflective structures in the eyes of moths act as regions of graded refractive index between the interface of the ambient medium and the surface of the eye. This allows moths to have almost no light reflected from their eyes, which helps them to avoid predators and survive for longer. By using a dielectric spacer layer between the moth-eye structures and the reflective back layer, we create locations for gap plasmons to be excited, leading us to almost perfect absorption from 400 to 1,600 nm with a variety of metallic materials.

We use double deep Q learning network (DDQN), to optimise the parameters of ultra-broadband, moth-eye structure perfect absorbers for several different metallic materials [1]. By exploring and exploiting important regions of the parameter space, the model quickly optimises the absorption of the structure and chooses the appropriate materials for the substrate and spacer layers to find the highest average absorption over the specified wavelength range, a schematic is shown in Figure 1. As the network learns the general relationships between each structural parameter, after training, the same network with the same weights and biases can be used again to optimise a new absorber with different optical properties.

2. Results and Discussion
From a random initial state, the DDQN was able to find parameters for absorption over 90% in almost every test episode, within around 100-200 steps. This is about $10^7$ times more efficient than a complete parameter sweep for each material.

To investigate the mechanism of the absorption of the device, we examined the power loss and studied the resulting electric and magnetic field responses at different wavelengths. The parabolic shape of the moth-eye structure creates a smooth gradient of refractive index, resulting in very low reflection that works in the visible range. There the power is absorbed on the surface of the moth-eye structure while the magnetic field has modes between moth-eye structures and around the tip. For longer, near-IR wavelengths, the electric field is strongly confined to the gaps between the moth-eye structures and the magnetic field becomes strongly confined to between the gaps of the structures. This can be attributed to gap plasmon resonances that can be supported by the highly lossy metals. The high-loss nature of these metals also helps to create the broadband absorber, as the resonances between the back-reflector layer and the moth-eye structures will have a low Q-factor, broadening the absorption further.

Figure 1 Schematic of the reinforcement learning environment and network.

References
Sensing Spatial Coherence of Light with Planar Metallic Metamaterials

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Abstract

We report on a discovery that homogeneous metallic non-diffracting metamaterials of a certain type respond differently to spatially coherent and incoherent light, enabling robust speckle-free discrimination between different degrees of coherence. The effect has no direct analogue in natural optical materials and may find applications in compact metadevices enhancing imaging, vision, detection, communication and metrology.

1. Introduction

Over the last decade the concept of artificially engineered media (now as metamaterials) has revolutionized the field of optics, pushed the boundaries of microfabrication and stimulated the development of novel characterization techniques. Recent demonstrations of anomalous reflection and refraction of light by metasurfaces opened another exciting chapter in optical engineering \[1\]. Non-diffracting metasurfaces correspond to a class of low-dimensional (planar) metamaterials and are typically formed by optically thin metal films periodically patterned on a sub-wavelength scale. Despite their vanishing thickness planar metamaterials interact strongly with light, which they can transmit, absorb or reflect without diffraction, effectively acting as optical media of zero dimension in the direction of light propagation. Metasurfaces have already enabled spectral and directional filtering, asymmetric transmission, polarization control and analysis, absorption enhancement imaging and sensing to name just a few, and are fully compatible with the existing fabrication processes adopted by CMOS technology.

2. Results and Discussion

Here we identify and investigate a class of trivial metallic planar metamaterials, which exhibit qualitatively different transmission in the near-IR when illuminated with, respectively, spatially coherent and incoherent light (as schematically shown in Figs. 1a and 1b). The underlying strongly non-local response of the metasurfaces involves \textit{neither diffraction nor lattice resonances}, which renders the reported effect as non-trivial \[2\]. Previously unseen in metamaterials the effect appears to be robust and exceptionally strong, and hence is immediately suitable for practical applications, such as optical metrology, imaging and communications.

![Figure 1: ZZnS metamaterial under spatially coherent (a) and incoherent (b) illumination. Red zigzag arrows represent non-dispersive resonant delocalised plasmon modes underpinning the effect. (c) Transmission spectra of the planar metamaterial measured under coherent (black crosses) and incoherent (solid blue line) illumination. Inset shows SEM image of the planar metamaterial; yellow box encompasses its translational unit cell; white arrow shows the polarization of incident light; scale bar corresponds to 1 \(\mu m\).](attachment:image.png)
Among the metasurfaces that have been found to discriminate between coherent and incoherent light are planar metamaterials featuring a continuous periodic zigzag pattern (see inset to Fig. 1c). The metasurfaces that we consider here were designed to operate in the near-IR part of the spectrum and composed of arrays of continuous zigzag nano-wires, as well as their inversion, i.e., continuous zigzag nano-slits. Both the nano-wires and nano-slits had the width of about 80 nm and were milled with a focused ion beam in an 80 nm thick film of amorphous gold that had been sputtered on 0.5 mm thick fused-quartz substrate beforehand. The resulting patterns had the period of 660 nm along the zigzags and 520 nm across the zigzags. The fabricated samples had the area of 21.1 µm x 20.8 µm, which encompassed a total of 1280 zigzag periods.

Our data suggest that those metasurfaces, while non-diffracting, can indeed behave differently under, respectively, incoherent and coherent illumination, exhibiting resonances with dissimilar profiles (Fig. 1). The systematic experimental investigation and rigorous theoretical analysis of this phenomenon (the results of which will be presented at the conference) indicate that it is a genuine, new optical effect that has no direct analogue in natural optical materials. The mechanism underpinning the effect involves interference of light scattered non-locally via non-dispersive delocalised plasmon modes uniquely supported by the fabric of the metasurfaces.

Acknowledgements

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References


Photothermal energy conversion in mid infrared metasurfaces

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Abstract

Mid infrared wavelength is unique to apply the detection of the small amount of molecules with molecular vibration or rotational modes. Especially absorption type of metasurface can be used for the mid infrared light source, detectors according to the Kirchhoff’s thermal radiation law. Here we summarized the recent progress of plasmonic metasurfaces in mid infrared wavelength region. The experimentally measured optical properties were compared with simulations by Finite difference time-domain calculations. Also, we demonstrate applications of these structures for the plasmonic IR-light sources and detectors and another sensing devices.

1. Introduction

The metasurface becomes essential material to control optical transmission, reflection and absorption. The absorption type of metasurfaces are consists of the thick metal layer - insulator layer - metal nano structures[1, 2, 3, 4]. Due to the bottom side of metal layer, there is no transmission has been allowed. When the plasmon resonance has occurred on the top nano structures, the mirror plasmon has generated on the bottom layer, and interaction between top nano structures and bottom layer has happened. Then reflection light has also suppressed with MIM structures. Therefore, strong electric field localization has happened especially at the insulator layer. Localized electromagnetic field is decaying due to the ohmic loss and generates the thermal energy. One of the popular trends of the application of metasurfaces is photo-thermal energy conversions. For example, solar light spectrum that reach to the surface of earth, from 400 to 2500 nm light has existing according to the radiation of 5600 K thermal radiation. For that purpose, the broad band photo generation is required in visible to near infrared wavelength for the solar application like solar cell enhancement, solar-thermal energy harvesting. The application of thermal radiation towards earth cooling required relative narrow band but specific wavelength condition is required. For example, the wavelength region that 0.2~1.2, 1.6~1.8, 2~2.5, 3.4~4.2, 4.4~5.5, 8~14 μm are so called the “atmospheric window”. that have no absorption region of H₂O, CO₂. Narrow band absorption is required for the mid infrared wavelength towards molecular sensing applications. On the other hands molecular vibrational modes have still more narrow band ≤ 20 cm⁻¹ in mid infrared wavelength, therefore it is important to realize further narrow band to identify the molecules with high accuracy (qualitatively and quantitatively). We have succeeded to realized narrower thermal radiation using metasurfaces as shown in figure 2.

In this presentation we will discuss the recent trends and our recent progress in metasurfaces.

2. Experimental methods for fabrication of mid infrared metasurfaces

The resonance wavelength of metasurfaces are strongly depends on the size, materials of metasurfaces and surrounding permittivity of metasurfaces. Also MIM type of structures, it is depends on the metal of substrate, insulator thickness, dielectric properties of insulators. From the our experiments and FDTD simulations, Au as the metal and SiO₂ as the insulator system is used for conventional metasurfaces. And realised 95% absorption with optimisation of the parameters as shown in figure 1.

Meta surfaces can be fabricate with the conventional lithography techniques, deposition of metal and insulator layer by sputtering or thermal/EB evaporation under high vacuum condition. After that nano structures has fabricated by the EB lithography. In the mid infrared wavelength region, the required sub-μm to μm size of structure. Therefore if the structures are simple circle, square, triangle, fab-
Optical reflection spectroscopy has been performed with the combination of the FT-IR (FT-IR 4200, JASCO CO.) and microscope unit (IRT-1000). As a reference for the reflectance spectra, a Au mirror with the 98% absolute reflectance has been used. For the thermal radiation spectroscopy, specially modified FT-IR system was implemented. The light from the outside was coupled into the FT-IR setup from an optical side port. The light passed through the interferometer and directed to the HgCdTe (MCT) detector. Samples were contacted to the ceramic heaters on an Al plate with ceramic glue.

3. Conclusions

In this presentation we will report the recent progress in the absorption type of metasurface including review of the main stream of this study and including our recent study. We have demonstrated the optical absorption properties of various kinds of plasmonic and label free absorbers in mid-IR wavelengths. Still further improvement is needed to realize real perfect absorber in mid infrared wavelength region. Mid infrared plasmonics and metasurfaces are interesting field for application of sensing and energy harvesting.

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References
Topological Pillared Phononic Crystals: Edge States, Fano Resonance and Their Robustness Against Disorder

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Abstract

We study theoretically the topological properties of pillared phononic crystals. By breaking the space inversion symmetry in a honeycomb lattice, we show different topological phases emulating the analogs of quantum valley and spin Hall effects. Robust edge states with one-way propagation are demonstrated as well as a rich variety of refraction phenomena at the outlets. A robust topological Fano mechanical resonance is achieved in a pillared beam from the superposition of a dark and a bright edge mode.

1. Introduction

Following a great deal of interest devoted to topological condensed matter physics and the demonstrations of one-way propagating edge states which are immune to disorder and perturbations, similar phenomena have been studied with classical waves such as in photonic and phononic crystals (PC). The manipulation of acoustic and elastic waves using the edge states at the interface of two topologically different phases has already been the object of several works. Plate structures provide an interesting platform for the manipulation of elastic waves, especially owing to their potential applications in the control of Lamb waves. In this frame, we present a review of our recent works [1-4] on pillared PC constituted by a periodic array of pillars on one side or on both sides of a thin plate.

We proposed pillared PCs during the last decade for taking advantage of their bandgaps which can originate either from the Bragg mechanism or from the local resonances of the individual pillars. In the latter case, the bandgaps can appear in the sub-wavelength range, hence being useful in the frame of acoustic metamaterials. In some of our recent works, we studied the topological properties of these structures [1-4]. A PC constituted by a honeycomb array of pillars on a plate can provide a Dirac cone at the K point of the Brillouin zone whose degeneracy can be lifted by breaking the space inversion symmetry. This can be done by introducing a dissymmetry between the two pillars in the unit cell, for instance by choosing slightly different diameters or heights.

When two such crystals belonging to two different topological phases are joined together, we can expect edge states with one-way propagation and robustness with respect to local disorder or defects. This can be already achieved with a single-sided pillar structure for the Aₜ Lamb modes [1]. But in order to create a complete bandgap at the level of the Dirac cone, we designed several two-sided pillar PCs, with possibly periodic holes between the pillars. Both symmetric [2] and asymmetric [3] pillars with respect to the middle plane of the plate were considered. Here we focus more especially on the former case which provides the possibility of considering separately the symmetric (S₀ and SH₀) and antisymmetric (Aₜ) Lamb modes.

The following issues have been addressed. First, we study the possibility of topological phases emulating the analogs of valley and spin Hall effects and the existence of edge states which are robust with respect to the presence of zigzag and defects; also, we show a variety of refraction phenomena when the edge states reach the armchair or zigzag outlets of the pillared structure. Then, we demonstrate the possibility of a topological Fano resonance in a pillared beam resulting from the superposition of a bright and a dark mode. In each part, we investigate the robustness of different topological edge states with respect to perturbations and disorder in the structure.

2. Results and discussion

2.1. Topological phases, edge states and their refraction at the outlets in pillared phononic crystals

The basic unit cell is constituted by a honeycomb lattice composed of two identical arrays of pillars over a thin plate and four perforated holes drilled at the corners of the unit cell (Fig.1a). Due to the symmetry of the structure, the dispersion curves (see an example in Fig. 1b) associated with symmetrical (S, red) and anti-symmetrical (AS, blue) Lamb modes can be considered independently of each other (Fig.1b). The geometrical parameters are chosen in such a way that, after breaking the space-inversion symmetry, the lifting degeneracy of the Dirac cones will open complete
band gaps [2]. By perturbing the diameters of the two pillars in the unit cell, one can achieve the analog of quantum valley Hall effect (QVHE) for both S and AS modes and the designed Dirac cones can be obtained both in the low frequency (deep sub-wavelength) or high frequency regimes. Robust one-way propagating edge states are obtained by joining together two crystals in topologically different phases. Considering the S modes in sub-wavelength regime, the refraction of the edge state at the exit of the waveguide turns to be evanescent at the zigzag termination and can be enhanced by a locally resonant mode. When occurring at high frequency, the refracted patterns (number, polarizations and angles of the refracted modes) can be tailored. Due to the proximity of Dirac cones for S and AS modes, the parameters can be designed to obtain a double Dirac cone at the K point of the Brillouin zone. This provides the possibility of emulating the analog of the quantum spin Hall effect (QSHE) and investigate the corresponding edge states. Furthermore, we demonstrate the occurrence of pseudospin-valley coupled edge states by assembling two PC supporting QSHE and QVHE respectively. This allows to take advantage of both pseudospin and valley degrees of freedom for the control of wave propagation. Figs. 1(c-e) give an illustration by considering the valley-dependent propagation at a T-junction of three PC supporting either QSHE or QVHE.

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2.2. Topological Fano resonance in a pillared beam

Fano resonance is a widely spread and basic kind of resonance that exhibits an asymmetric line shape with an ultra-high quality factor Q. It usually requires delicate designs and precise fabrication. By considering a mechanical beam supporting symmetrically two-sided pillars, we achieved a robust Fano resonance with topological protection [4]. This is obtained by engineering band inversion of two different vibrating symmetries of the pillared beam that gives rise to a dark and a bright edge mode [4]. The Fano resonance results from the constructive and destructive interferences between topological dark and bright modes, as seen in Fig.2. It is further demonstrated that the Fano asymmetric shape of the transmission peak and its frequency remain robust against random disorder in pillars’ position as long as the symmetry with respect to the mid-plane of the plate is conserved. If the random perturbations break this symmetry while conserving only band inversion, the asymmetric line shape of the Fano resonance weakens until disappearing before the closure of the bulk band gap. Indeed, after symmetry breaking, the incident excitation will couple all fundamental modes of the beam. The analysis of the robustness of Fano resonance originating from band inversion and symmetry protection reveals the nature of topological protection which can be applied to design topological high Q resonance in sensing applications.

Figure 1: (a) Elementary unit cell and (b) its band structure. Red and blue curves correspond to symmetric (S) and anti-symmetric (AS) modes. (c) Schematic of the T-junction and the valley-dependent propagation while the edge states are locked to (d) the valley K and (e) K̅ [2].

Figure 2: A Topological Fano resonance results from the interference between topological dark and bright modes [4].

References


A New Type Terahertz Quantum Cascade Laser Using Graphene-based van der Waals Heterostructures

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Abstract

This paper reviews recent advances in the research for graphene-based van der Waals heterostructures towards a new type of terahertz (THz) quantum-cascade lasers.

1. Introduction

Graphene has been attracting considerable attention due to its gapless and linear band structure offering massless Dirac fermions and plasmons [1]-[3]. Current-injection or optical pumping makes population inversion of graphene carriers enabling lasing and/or amplification of terahertz (THz) radiation [4],[5]. We’ve recently demonstrated 1-8-THz broadband amplified spontaneous THz emission as well as single-mode THz lasing at 5.2 THz both at 100K [6]. Present issues of poor gain overlapping and poor quantum efficiency (limited by the interband absorption coefficient of 2.3%) [6]. Introduction of a gated double-graphene-layered (G-DGL) van der Waals heterostructure in which gate-bias tuned THz radiation emission is obtained via plasmon- and/or photon-assisted quantum-mechanical resonant tunneling is a promising rout to further increase operation temperature as well as output intensity (Fig. 1) [7],[8]. Moreover, a vertical G-DGL cascade structure offers quantum-cascade multiplication of the THz gain, leading to a new type of THz quantum cascade lasers (QCLs) [10].

2. Device Structure and Physics

The important physics behind is the acoustic plasmon modes in the DGL that can enormously enhance the quantum efficiency by orders for conversion of dc electric power to THz photon radiation power in comparison with that for a simple graphene-channel transistor laser structure (Fig. 1) [7],[8]. We experimentally demonstrated the proof of concept of such an operation mechanism (Fig. 2) [9]. We have proposed a cascading of the G-DGL unit element working as a new type of THz quantum-cascade lasers (Figs. 3 and 4) [10]. The laser cavity can be structured along with the in-plane direction of the G-DGL mesa structure. The vertical G-DGL cascade structure (Fig. 3) can enlarge the mode field of the THz photon radiation to match the free-space impedance. Each DGL is also separated by a thin dielectric layer working as the carrier injector to the next DGL. An extended thick dielectric layer on top works for the surface plasmon waveguide.

Figure 1: G-DGL structure, photon-assisted tunneling, plasmon-assisted tunneling, and its plasmon modes [7,8].

Figure 2: Fabricated G-DGL and measured emission spectra at 100K under different gate bias conditions [9].

Figure 3: G-DGL Cascade Structure for a new type of graphene THz QCL [10].
We numerically analyzed the frequency dependence of the modal gain (Fig. 5) and spatial distributions of the THz photon electric fields in the TM modes of the surface plasmon waveguide (Fig. 6) of the device having different N values. As seen in Fig. 5, the modal gain is higher for structures with a small number of GL pairs in the low THz frequency region. This is because for low frequencies Drude absorption increases faster than the gain with an increase in the number of GL pairs. The situation is inverted for high THz frequency region. The increase in N above the frequency-dependent threshold values leads to increase in Drude absorption and reduction in modal gain. The results indicate that there exist optimal N value depending on frequency of operation.

As seen in Fig. 6, the THz photon electric field components in the TM mode of a surface plasmon waveguide at 5 THz in the device exhibit distinctive field distributions. The vertical electric field Ez responsible for the inter-GL tunneling gain is dominantly localized near the multiple-DGL’s region. The lateral component Ey responsible for the surface plasmon waveguiding is, on the contrary, localized at the topmost air/dielectric interface. Increasing the number of DGL’s cascade and, hence, the height of metal contacts, one increases the gain due to inter-GL tunneling transitions. On the other hand, the topmost DGL are located closer to the maximum of in-plane field Ey, and increase in the number of DGL’s can significantly increase ohmic losses (due to both Drude and interband absorption).

3. Conclusions

Recent advances in the research of graphene-based van der Waals heterostructures for THz laser device applications were reviewed. We have proposed a cascading of the G-DGL unit element working as a new type of THz QCL’s. Numerical analyses demonstrated further increase of the quantum efficiency of THz lasing by orders of magnitude in comparison with a GFET or single G-DGL structure. Experimental verification is now undergoing. Our proposed DGL-based THz QCL’s will open a promising route to the creation of room-temperature-operating current-injection-type integrated THz lasers.

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References

Optical Waveguide Using Off-Γ Bound States in the Continuum in One Dimensional Grating Structures

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Abstract
Bound states in the continuum (BICs) are exotic resonance modes that are localized states within radiation continuum. Especially, off-Γ BICs attract lot of attentions from researchers due to its intriguing features such as topological protection and steering ability. We proposed and numerically investigated filtering waveguides using off-Γ bound states in the continuum (BICs) in one dimensional grating structures. By using propagating feature of off-Γ BIC, light transmission is guided only around the BIC frequency without radiation leakage. The designed structure is composed of Si grating structure integrated with optical waveguide. Numerical simulations confirm the proposed filtering function at off-Γ BIC frequency.

1. Introduction
Bound states in the continuum (BICs) are exotic resonance modes that are localized states within radiation continuum. Although BICs have been initially introduced in quantum mechanics by von Neumann and Wigner, BICs can be observed in photonic systems including photonic crystals, metamaterials, and so on [1,2]. BICs in photonic system are confined modes without any radiation loss although the modes exist within the radiation continuum above the light line. Interestingly, there are two types of photonic BICs: one is at-Γ BICs (symmetry protected BICs), and the other is off-Γ BICs (accidental BICs) which appear at non-symmetric points in k-space. In contrast to at-Γ, off-Γ BICs recently attract lot of attentions from researchers due to its intriguing features such as topological protection and steering ability [3].

Since off-Γ BICs have a finite in-plane wave number (different from the symmetry points), which means off-Γ BICs can have a finite group velocity and thus can propagate in the slab. In this study, we propose and numerically investigate a new type of filtering waveguides by using off-Γ “propagating” BICs in one dimensional grating structures. Figure 1 shows the concept of the proposed waveguide. A grating structure is connected to input and output waveguides. When the frequency of light is within the radiation continuum above the light line, optical energy is generally dissipated due to the radiation loss during propagation, resulting in low transmittance. On the other hand, when the frequency of light is at the off-Γ BIC, the all optical energy transmits through the grating since there is no radiation leakage. Therefore, the waveguide works as a filtering waveguide operating at the off-Γ BIC frequency.

2. Off-Γ BICs in one-dimensional grating structures
Figure 2 shows the designed Si grating structure, band structures, and Q-factors. Numerical simulations were carried out by using a commercial finite-element-method solver (COMSOL). The simulated model is two dimensional and TM modes ($E_x, H_y, E_z$) are considered. The refractive indices of the grating and surrounding medium are 3.47 (Si) and 1 (Air), respectively. As shown in Figs. 2(b) and 2(c), at $k_x \sim 0.8\pi/a$, the Q-factor sharply increases at around 190 THz although this point is above the light line, which means that this mode corresponds to the off-Γ BIC. The radiative loss is accidentally suppressed at this k-point, resulting BIC with infinite Q-factor.
3. Off-Γ BIC filtering waveguide

Here we investigate the same grating structure integrated with simple Si waveguides for input/output. Figure 3(a) shows the simulation model of the off-Γ BIC waveguide. The input light is injected from the port 1 and the transmitted light is detected by port 2. Figure 3(b) shows transmission spectra with varying the length of the grating region \( l_{WG} \). Generally, the transmission intensity decreases as \( l_{WG} \) becomes longer because of the radiation loss in this frequency range. However, the transmission value at the off-Γ BIC frequency around 190 THz does not change even when the \( l_{WG} \) increases, which confirmed the expected filtering function of the proposed waveguide. The \( H_y \) distributions (Fig. 3(c)) shows that there is no radiation in the case of off-Γ BIC frequency, although one can see significant radiation flow at other frequencies, indicating a large radiation loss. In the presentation, we will discuss the effect of finite grating length in actual devices on performance of the filtering waveguide.

![Figure 2](image2.png)

**Figure 2:** (a)The designed grating structure. \( a = 885.5 \) nm, \( w = 266 \) nm, \( h = 250 \) nm, \( l = \infty \) (2D simulation). (b) TM band structure and (c) Q-factors.

4. Conclusions

We proposed and numerically investigated the filtering waveguide using off-Γ BIC in one dimensional grating structures. The structure in composed of Si grating and simple waveguide, and only the light with off-Γ BIC frequency can transmit through the waveguide without any radiation leakage, which confirmed the proposed filtering mechanism by using off-Γ propagating BICs.

![Figure 3](image3.png)

**Figure 3:** (a) Grating integrated waveguide structures modeled in 2D simulation. (b) Transmission spectra with changing \( l_{WG} \). (c) \( H_y \) distributions at in-band and off-Γ BIC frequencies.

Acknowledgements

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References

Slow-light dissipative Kerr solitons in coupled-cavity waveguides

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Abstract

We study frequency combs and dissipative Kerr solitons in silicon coupled-cavity waveguides (CCW) with globally optimized dispersion at telecom wavelengths. The corresponding threshold for comb generation is found to explicitly depend on the main CCW figures of merit, namely, mode volume, normal mode quality factor and slow-light group index. Our results set the CCW as a new paradigm for low-threshold comb generation via advanced dispersion engineering and slow-light enhancement.

Kerr frequency combs have been focus of intense research during the last decade since they were proposed for first time in monolithic microresonators as an appealing alternative to generate a spectrum of equally spaced frequency peaks, allowing an enormous reduction of size and power consumption with respect to their mode-locked lasers counterparts [1]. To date, they have impacted several fields in science where sophisticated frequency-comb-based technologies have been successfully established, such as ultra-high precision spectroscopy via dual-comb generation [2], massively parallel coherent telecommunications [3], sub-micrometer optical distance ranging at very high speeds [4], optical clocks [5] and precise calibration of astronomical spectrometers with astrocombs [6]. These applications rely on the emergence of a very special type of self-organized structures called dissipative Kerr solitons (DKS), which are the product of a cooperative interaction between a high number of modes in ring resonators [7]. DKS are efficiently generated in presence of anomalous dispersion, thus demanding a careful optimization of the photonic nanostructure. Nevertheless, the ring resonator geometry has a very limited parameter space to carry out advanced dispersion engineering, and hence the choice of materials and operation wavelength may be quite restricted in these systems.

In this work, we close the gap between frequency comb generation and advanced dispersion engineering by proposing the coupled-cavity waveguide (CCW) as a new system to support low-threshold DKS, where slow-light plays a fundamental role on enhancing the effective material non-linearity [8]. We derive from first principles a set of coupled-mode equations to describe the non-linear interaction between the Bloch modes of the CCW system in presence of Kerr non-linearity and two-photon absorption. The internal mode threshold for comb generation is found to be (in W units):

$$|A_p|^2 \text{th} = \frac{n_0^2 V_c}{2l n_g Q_p} \frac{1 + \kappa^2 + 2\kappa}{1 - 3\kappa^2},$$

where $n_0$ is the refractive index of the material, $V_c$ the non-linear cavity volume, $l$ the waveguide period, $n_2$ the Kerr coefficient, $n_g$ the group index, $Q_p$ the quality factor of the driven Bloch mode $p$ with frequency $\omega_p$, and $\kappa = c/\beta_{\text{TPA}}/2n_2\omega_p$, with $\beta_{\text{TPA}}$ representing the TPA coefficient. We apply our formalism to the photonic crystal (PhC) CCW shown in Fig. 1, formed by 400 coupled L3 cavities with optimized first and second neighbor coupling to induce a waveguide mode displaying anomalous dispersion, large group index and low out-of-plane losses at telecom wavelengths [9]. Figure 2(a) shows the averaged waveguide power as a function of the laser detuning $\sigma = \Omega_0 - \omega_p$ in $\gamma_p = \omega_p/Q_p$ units. We clearly identify a sequence of discrete steps which are the signature of the switching between different soliton states. We show in Fig. 2(b) the envelope function associated to the single pulse soliton, whose spectrum, shown in Fig. 2(c), has a single FSR spacing as expected from the DKS theory.

Our results thus set the CCW as a new paradigm for low-threshold comb generation via advanced dispersion engineering and slow-light non-linear enhancement.

References

Figure 1: (a) Intensity profile of the fundamental waveguide mode. Red and blue holes are varied to optimize the photonic dispersion, while the yellow ones are varied to optimize the out-of-plane losses. (b) Dispersion of the system in (a) with the anomalous dispersion region highlighted in blue.

Figure 2: (a) Average waveguide power as a function of the laser detuning. (b) Real-space envelope function (along the PhC-CCW) of the soliton marked in (a). (c) Corresponding frequency comb of (b).


Characterization of mid-IR photonic crystal slabs using angle-resolved FT-IR spectroscopy

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Abstract

Fourier transform (FT) spectroscopy is a versatile technique to study the infrared (IR) optical response of solid-, liquid-, and gas-phase samples. Here we design and construct a high-precision angle-resolved reflectance setup compatible with a commercial FT-IR spectrometer. As a demonstration of the capability of the reflectance setup, we measure the angle-dependent mid-infrared spectra of two-dimensional photonic crystal slabs, and determine the in-plane photonic band dispersion in the vicinity of Γ point in momentum space.

1. Introduction

Fourier transform infrared (FT-IR) spectrometer is a ubiquitous spectroscopic tool used for broad area of material research. In standard FT-IR spectrometers, a light beam passing through a Michelson interferometer focuses on a sample with condenser optics. Such design enables us to examine relatively small samples with a sufficient throughput, but the large solid angle of the focused infrared beam makes it difficult to analyze angle-dependent characteristic. Hence, the standard FT-IR could fail to analyze the angular dependent optical response inherent in anisotropic samples, which include photonic crystal (PC) waveguides and plasmonic meta surfaces.

To overcome this problem, we design and construct an angle-resolved infrared reflection setup with two design objectives. The first objective is to achieve a good collimation for the incident beam whose incident angle is tunable across zero, i.e., the normal incidence angle. The second design objective is a small footprint, so that the setup can smoothly be installed in the sample room of standard FT-IR. As a demonstration of the capability of the reflection setup, we measure the angle-dependent mid-infrared reflectance spectra of two-dimensional photonic crystal slabs, which are fabricated on silicon-on-insulator (SOI) substrates, and InP based InGaAs multiple quantum well (MQW) structures.

2. Result and discussion

2.1. Reflection setup design

We use Jasco FT/IR6800, which has a maximum spectral resolution of 0.07 cm⁻¹. The spectrometer incorporates a liquid nitrogen cooled mercury cadmium telluride (MCT) detector, which has a good sensitivity between 650 to 12000 cm⁻¹.

Figure 1 shows the optical diagram of the angle-resolved reflectance setup. The infrared beam from the spectrometer is reflected from a flat steering mirror M1 to an off-axial parabolic mirror PM1 that has an effective focusing length of 25.4 mm (Thorlabs, MPD019-M01). PM1 collimates the beam and sends it to another steering mirror M2. The beam is then directed to a 50:50 calcium fluoride beamsplitter (BS; Thorlabs, BSW510 for wavelengths of 2 - 8 μm).

![Figure 1: The optical diagram of the angle-resolved reflectance setup. The dash dotted line shows the optical axis.](image-url)
The beam transmitted through the BS is incident on the sample, which is mounted on a micrometer driven rotary stage. The sample reflects the beam, and brings it back to BS, which reflects it to a movable mirror M3. The M3 motion fully compensates beam shifting with changing the incident angle: When the sample is rotated by $\theta$, M3 should be rotated by $-\theta$ and adequately translated, which keeps the beam on axis after M3. Then, the beam is passed through M4, PM2 and M5, which is identical with M2, PM1, and M1, respectively, towards the instrument detector.

All the optics are arranged on a 150 mm x 250 mm aluminum breadboard, which can smoothly be installed in the sample chamber of FT-IR, see the setup photograph in Fig. 2. Currently, the maximum tunable range in the incident angle is $+\pm 3.7$ degree, which is limited by the size of BS (25.4 mm in diameter) and the M3 translator travel (25 mm). With future minor changes, the tunable range would easily be extended.

2.2. PC slab characterization

2.2.1. Mid-IR Dirac cones in SOI based PC slab

We applied the reflectance setup to demonstrating the formation of photonic Dirac cones in SOI based PC slabs. For this purpose, we conducted finite-element calculations to find a PC parameter that leads to accidental degeneracy at $\Gamma$ point, fabricated the samples with EB lithography, and measured the polarized reflectance spectra, which revealed the formation of photonic Dirac cones at Mid-IR regions [1].

2.2.2. PC slabs on InP based MQW structures

We fabricated PC structures on InP based quantum cascade laser (QCL) devices. Here, the $\Gamma$ point frequency is resonant with the QCL output frequency, as was confirmed by the reflectance spectra in Fig. 3. Hence, we can expect the operation of vertical surface emission in mid-IR QCL.

3. Conclusions

Various types of photonic systems, which include PC waveguides and plasmonic meta surfaces, require spectral characterizations with high angle resolutions. Here we proposed, and successfully demonstrated an approach to measure mid-IR angle-resolved spectra. The technique is useful and flexible, as it utilized a standard FT-IR.

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References

The Revolutionary Advent of Magnetless Nonreciprocal Metasurfaces
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Abstract

We present a narrative overview of our work on magnetless nonreciprocal metasurfaces over the past decade, showing how the spacetime telescoping of the two emerging areas of magnetless nonreciprocity and metasurface transformation has lead to the revolutionary technology of magnetless nonreciprocal metasurfaces.

1. Introduction

A bit more than ten years ago, we asked whether metamaterials could provide a solution to the long-standing issues of ferrite-based nonreciprocal devices, including foremost their crystallographic incompatibility with semiconductors. We came up with a positive answer to this question in 2011 [1], but our progress in this area has next been severely impeded by a lack of both physical understanding and engineering modeling of such “magnetless metamaterials”. The situation has dramatically changed with recent advances in metasurfaces, the two-dimensional counterparts of voluminal metamaterials.


Nonreciprocity, defined as the property according to which a system exhibits different transfer properties when its source and detector are exchanged, is an ubiquitous concept in science and technology. Its scientific foundations were laid out by illustrious scientists such as Faraday, Stokes, Helmholtz, Kirchhoff, Rayleigh, Planck, Onsager, Casimir and Tellegen in the period extending from the mid 19th century to the mid 19th century, and its technological applications have enabled uncountable microwave and optical systems since WW-II.


Over the past 70 years, or so, to date, nonreciprocal devices have been exclusively based on ferrimagnetic material and permanent magnet technology. Unfortunately, this technology suffers from a series of issues, including, in addition to incompatibility with semiconductors, material brittleness and corrosiveness, magnet bulkiness and heaviness, functionality limitation, demagnetization hazards, injury danger, polluting extraction and uneven geopolitical distribution. More than enough issues to make magnetless nonreciprocity a “Holy Grail” for scientists and engineering!

Fortunately, metamaterials can indeed be engineered to exhibit the same properties and then provide the same devices as – and more than! – ferrites, without requiring any ferrimagnetic substances and magnet. Such metamaterial magnetless nonreciprocity is illustrated in Fig. [1] where a typical nonreciprocal device is realized by a magnetless metamaterial composed of unidirectional (typically transistor-loaded) ring particles that mimic electron spin precession in real magnetized magnetic materials [14, 5].

![Figure 1: Metamaterial magnetless nonreciprocity. (a) Magnetless circulator. (b) Realization of (a) using unidirectional ring metaparticles.](image)

We have experimentally demonstrated this technology in a number of applications, including isolators and circulators [6], switchable Faraday rotators [7] and nonreciprocal antennas [8], but these devices were essentially restricted to one-dimensional structures with limited properties.

4. Magnetless Nonreciprocal Metasurfaces

Recent developments in metasurfaces provide the missing link for a paradigm shift in magnetless metamaterial technology for unprecedented spatial and temporal electromagnetic wave transformations [9, 10]. Indeed, metasurfaces possess up to 36 bianisotropic susceptibility parameters that may be engineered for virtually unlimited wave magnitude, phase and polarization manipulations, and powerful modeling tools, based on the Generalized Sheet Transition Conditions (GSTCs) (extension of the conventional electromagnetic boundary conditions including surface polarizations) have been elaborated for their design [11, 12, 13].

Whereas the early magnetless nonreciprocal (gyrotropic or nongyrotropic) metasurfaces were restricted to basic operations such as Faraday rotation [1] or isolation [14], leveraging the most advanced metasurface concepts enriches nonreciprocity by the aforementioned diversity of properties, and hence leads to revolutionary electro-
magnetic devices. An example of such a device is depicted in Fig. 2, where time reversal symmetry is broken in such a way that it produces a most unusual effect of rectilinear Faraday rotation in one direction and nongyrotropic spatial angular deflection in the opposite direction.

(a)

(b)

Figure 2: Example of a magnetless nonreciprocal metasurface. (a) Rectilinear Faraday rotation of a wave propagating from the left to the right. (b) Nongyrotropic spatial angular deflection of wave resulting from (a) upon reinjection into the system in the opposite direction.

The design of such metasurfaces requires a deep understanding of the physics of nonreciprocal systems and solid modeling techniques, both of which we believe, becoming available at this point of spacetime [15, 16, 17, 18]. We shall demonstrate this concretely at the conference.

References


Metasurface-Enabled 3-Dimensional Structured-Light Imaging

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Abstract
We have demonstrated compact structured-light projectors for 3D-depth imaging. The projectors are made by integrating metastructures directly on a DFB LD and a VCSEL array. The metastructures are subwavelength dielectric nanostructures that allow very precise, versatile wavefront manipulation. They serve as a single-element solution that provides precise control of phases and amplitudes, and the nanoscale size allows a wide field-of-view in a smallest form-factor possible. The fabrication of the metasurfaces utilizes well-established semiconductor-processes and promises low-cost mass-production for mobile applications.

1. Introduction
Flat dielectric metasurfaces could provide practical optical elements for developing a variety of new compact optical platforms. As metasurfaces are highly compatible with the materials and the nanoscale fabrication technologies of the semiconductor industry, innovative optical devices have started to emerge by flattening conventional optics while at the same time introducing and integrating new optical functionalities [1-3]. A structured-light (SL) projector is a 3D depth camera which could greatly benefit from the dielectric metasurfaces. Compared with conventional SL projectors, utilizing a metalens as a single-element solution provides compact, highly-efficient, and production-friendly modules, whose size, cost, and power consumption are critical consideration factors for the use in future mobile 3D camera applications. We present two metasurface-based projector solutions, one using a distributed feedback (DFB) laser diode (LD) and the other using a VCSEL array as a light source.

2. Diffractive Metasurface SL projector with a DFB LD
Using a diffractive metasurface and a DFB LD, we have generated a high-quality pattern used for SL. Figure 1(a) shows the schematic diagram of an SL projector made of a metasurface lens, a DFB LD, and a beam-reflecting mirror all assembled in a compact housing. The reflecting mirror is used to redirect the laser emission from the edge of the DFB LD onto the metasurface. Please note that using the mirror in this configuration makes the reflected light to enter the metasurface lens at an angle but allows us to minimize the height of the projector and achieve the smallest form possible. If packaged properly, the total height of the projector can be less than 2 mm. Due to the oblique incident angle, the diffractive metasurface was designed using computer-generated holography (CGH) technique with an off-axis reference-light illumination. The metasurface is made of nanopost-shaped amorphous Si (a-Si) meta-antennas, and its transmitted wavefront follows the CGH-designed phase profile. Because the metasurface generating the SL pattern is working as a hologram, it is highly dependent on the light source and optical alignment. Therefore, an active alignment method along the four axes is required when assembling and aligning the metasurface with regard to the laser propagation. The field-of-view (FOV) is as large as 80° with an efficiency exceeding 80%. In Fig. 1(b), the projected SL dot patterns are shown, where the dots are clearly defined at the center (left) and edge (right) over the whole FOV.

3. Metalens SL projector with a VCSEL Array
By designing a metalens to have a flat, aspheric phase transmittance and using a VCSEL array as a light source, an imaging-type SL projector can be created (Fig. 2). In Fig. 2 (a), at the bottom and on the top surfaces of a glass substrate, a metal mask and a metalens are formed, respectively. The mask defines the original pattern of the SL to be projected by incident light from the VCSEL array and the metalens at the top surface of the glass substrate. The distance between the mask and the VCSEL array is set to form a uniform illumination at the mask surface by the propagation of laser light emitted from the VCSEL arrays. The metalens is designed to deflect and project the propagating light passing through the bottom mask patterns over the entire FOV of about 80°. Just like the diffractive metasurface used with the DFB LD, the metalens also consists of an a-Si metal-antenna array specifically designed to have high efficiency over a wide range of deflection angles. Note that the height of this imaging SL projector is also around 2 mm. Since the mask and metalens are integrated as a single optical element, the module assembly of the element and the VCSEL array becomes a simple task.
Figure 1: Diffractive metasurface SL projector with a DFB LD (a) a schematic diagram of the projector and a SEM image of the diffractive metasurface (b) the projected SL’s dot patterns at the center (left) and edge (right) of the FOV.

Figure 2(b) shows a SL pattern projected by the device on a real object statue (at the left) and a 3D depth colormap image (at the right) obtained by running an SL-depth-extraction algorithm on the captured pattern image. We were able to reconstruct a high-resolution depth image. The defects at the edges of the image are due to misalignment of the projector and imaging camera optics.

4. Conclusions

Metasurface manipulates optical wavefronts by utilizing subwavelength sampling and modification performed by a dense array of precisely designed antennas. It can provide a highly sophisticated light control using a single layer of surface structures. This provides a great advantage and resolves various design challenges involved in developing a SL projector for use as a smartphone depth camera because it provides an extremely small form-factor, simple assembly, mechanical robustness/reliability, low-cost batch fabrication, and most of all, efficient projection of high-quality SL patterns.

References


Scattering properties of Parity-Time symmetric chiral metamaterials

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Abstract
Combining parity-time (PT) symmetry and chirality in the same system one can achieve a variety of novel electromagnetic properties and effects. Here we demonstrate some of those effects in a simple bi-layer PT-symmetric chiral structure illumined by a plane wave. Phenomena such as unidirectional reflectionless propagation, asymmetric transmitted wave ellipticity and optical activity, mixed PT-related phases, simultaneous coherent perfect absorption and lasing of circularly polarized waves, etc., are numerically demonstrating. All those phenomena, realizable with realistic chiral metamaterials, empower PT-symmetric chiral systems with unique possibilities regarding electromagnetic wave control.

1. Introduction - System
PT-symmetric optical systems have attracted recently a great degree of attention [1,2]. This attention stems not only from their novel properties and effects (i.e. unidirectional invisibility, simultaneous coherent perfect absorption (CPA) and lasing, loss-induced transparency, etc.) but also from the possibility that they offer for practical realization and control, unlike their quantum mechanical counterparts. Optical PT-symmetric systems, requiring refractive index, \( n \), fulfilling \( n(-r) = n^*(r) \) (or, in the more general case, permittivity, \( \varepsilon \), and permeability, \( \mu \), fulfilling a similar condition), can be relatively easily realized in practice by proper combination of loss and gain in the same system. In many cases for this practical realization one has to resort to metamaterials. Combining PT-symmetry with metamaterials not only can allow the realization of many desired PT-symmetric systems but it also expands greatly the novel EM phenomena and the possibilities offered by such systems. An example is the combination of PT-symmetry with metamaterials of permittivity or permeability near-zero, which allowed the achievement of peculiar surface states, uncommon tunneling effects etc.

One category of metamaterials which is still highly unexplored under the concept of PT-symmetry is chiral metamaterials, i.e. metamaterials where the structure lacks any mirror-symmetry. Such metamaterials are associated with strong magnetoelectric coupling (i.e. excitation of electric (magnetic) polarization by a magnetic (electric) field), leading to different index of refraction for left- and right-handed circularly polarized waves (denoted here by LCP (or -) and RCP (or +), respectively), and as a result to interesting polarization-control-related phenomena [3]. Among such phenomena of particular interest is the polarization rotation of a wave passing through a chiral medium (known as optical activity) and the absorption difference between LCP and RCP waves, resulting, e.g., in transformation of a linearly polarized wave passing through a chiral structure to elliptically polarized.

\[ \varepsilon(-r) = \varepsilon^*(r), \mu(-r) = \mu^*(r), \kappa(-r) = -\kappa^*(r) \quad (1) \]

In (1) the parameter \( \kappa \) is the parameter quantifying the magnetoelectric coupling in the constitutive relations for...
chiral metamaterials [3]; thus it is the main parameter responsible for the polarization-related properties of chiral metamaterials.

In this work we consider a simple bi-layer chiral metamaterial structure (see Fig. 1) fulfilling conditions (1), and we investigate its scattering properties and the novel wave phenomena realizable by this structure. The investigation is based on the calculation of the scattering matrix of the structure for circularly polarized incident waves under both normal and off-normal incidence and the examination of its eigenvalues along with the transmission, reflection and the polarization characteristics of the transmitted waves. In the case of open (scattering) PT-symmetric systems it has been shown that the scattering matrix eigenvalues are the quantity that can offer information about the different PT-related phases achievable in those systems, i.e. the full PT-symmetric phase (where the system behaves mainly as Hermitian; there the scattering matrix eigenvalues are unimodular), the PT-broken phase (associated with dominance of gain or loss and with non-unimodular eigenvalues) and the exceptional point (EP), a singular point where two or more eigenvalues and eigenvectors coincide and many peculiar effects can be observed.

2. Results

Investigating the structure of Fig. 1 in the case of normally incident waves one can find that the scattering matrix eigenvalues and all the PT-symmetry related characteristics are totally independent of chirality. On the other hand, the transmitted wave ellipticity (quantifying the circular dichroism) depends exclusively on chirality and is independent of $\varepsilon$ and $\mu$. Thus, if one has the ability to control the chirality ($\kappa$) of a structure independently of its permittivity and permeability, as is highly possible in the case of chiral metamaterials, one can combine and superimpose at will the PT-symmetry-related novel effects (such as exceptional points, CPA-laser points) with desired polarization characteristics. Such a possibility can have a great impact in propagation and polarization control-related phenomena and applications.

In the case of off-normal incidence the above mentioned independency does not hold anymore but it gives its position to a great variety of PT- and polarization-related characteristics [5]. Such characteristics include (a) the existence of mixed phases and multiple exceptional points [6] (see Fig. 2(a)), (b) asymmetric (i.e. side-dependent) cross-polarized transmission for linearly polarized incident waves, (c) asymmetric transmitted wave ellipticity and optical activity (see Fig. 2(b)), and others. All those effects are chirality-dependent and, more importantly, incidence-angle-dependent. The incidence-angle dependence gives the possibility for an easy external control of almost all the PT- and propagation-related characteristics of PT-symmetric chiral systems, entailing unique possibilities in polarization control applications and devices, such as polarization isolators, polarization filters, wave plates, etc.

Figure 2: (a): Scattering matrix eigenvalues ($\sigma$) for the PT-symmetric bilayer of Fig. 1, for incidence angle 45°, as a function of the dimensionless frequency $\omega a/c$. The material parameters for the loss material of the system are $\varepsilon_R=4+0.4i$, $\mu_R=2+0.1i$, $\kappa_R=0.04-0.01i$ (see Fig. 1 caption). (b): Optical activity ($\theta$) for a TM linearly polarized wave incident on the system of (a) from the left-side (black-solid line) and the right-side (red-dashed line). $L$ is the system length and $c$ the vacuum speed of light.

3. Conclusions

We performed a detailed investigation of wave scattering by PT-symmetric chiral structures. This investigation led to the demonstration of a variety of novel effects and properties, including multiple exceptional points, mixed PT phases, and asymmetric and incidence-angle-dependent transmitted wave intensity and polarization. All those effects imply unique possibilities for EM wave propagation and polarization control, allowing, e.g., angle-tunable polarization isolation and filtering, angle controllable CPA-lasing for circularly polarized waves etc.

Acknowledgements

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References

Field-Ready Quantum Technologies based on Nanowire Sources

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Abstract

Quantum technologies based on semiconductor quantum dots placed in photonic nanowires are discussed. Epitaxial growth strategies of the embedded dots targeting field-appropriate wavelengths are presented. The tapered shape of the nanowires allows for direct and evanescent coupling to bulk and integrated optics, respectively. This enables a high degree of photonic integration aimed at deploying plug-and-play quantum systems to the field for applications in secure communications, sensing and metrology.

1. Introduction

Bright, high purity sources of single and entangled photons are a necessary resource in realizing quantum supremacy over conventional technologies based upon classical physics. A promising candidate for such sources are semiconductor quantum dots embedded in nanowires [1,2]. In the work presented here we discuss the design and realization of InAs-InP semiconductor quantum dot sources in which the emitter is placed along the axis of a wurtzite InP nanowire. Growth by chemical beam epitaxy (CBE) is performed in two phases: a site-selected vapor-liquid-solid

Figure 1: (a) Nanowire post-growth. (b) Power-dependent spectrum. (c) Multiphoton coincidence measurement.

(VLS) phase of the InP nanowire core and InAs quantum dot followed by a radial growth phase that forms the optical cladding and inverse taper. Figure 1a shows a SEM image of a nanowire with an associated power-dependent emission spectrum presented in figure 1b. A multiphoton coincidence measurement showing a high degree of single-photon purity of the nanowire emission can be seen in Fig. 1c.

2. Source Design

Modification of the dot growth conditions allow for emission wavelength tuning from approximately λ = 880 nm to beyond λ = 1500 nm, as shown in Fig. 2a [3]. Shifting to longer wavelengths, however, results in a considerable decrease in emission rate. Reasons why this occurs and methods to mitigate this will be discussed. An attractive feature of this bottom-up approach is that multiple quantum emitters can be placed at deterministic spacings in a single nanowire, as shown in Fig. 2b [4]. This allows for highly integrated multiplexed sources of single photons.

Figure 2: (a) Growth tuning of dots from 800 nm to telecom wavelengths. (b) Multiple emitters in a single nanowire.

3. Photonic Integration

Photons emitted from the embedded quantum dot couple into the Gaussian-like HE₁₁ mode of the nanowire waveguide. The effects of taper length and angle on the numerical aperture of the nanowire source are shown in figure 4. With appropriate taper design, efficiencies in excess of 90% can be achieved for coupling of the HE₁₁ mode to single mode optical fibre [5]. The nanowire numerical aperture design can be made to match a GRIN lens assembly targeting single and entangled photon plug-and-play applications. Figure 5 shows an example of such an assembly and the associated single-photon collection. The tapered nature of the InP nanowire described above produces an expanding, less confined optical mode as photons propagate towards the nanowire tip. If the nanowire is brought into the vicinity of a SiN waveguide, photons can be transferred from the nanowire, into the waveguide and can be made available for further processing as part of a...
photonic integrated circuit [6]. Such a coupled nanowire-waveguide is shown below in Fig. 6.

![Figure 4: Numerical aperture achievable for a given taper length and acceptance angle.](image)

**Figure 4:** Numerical aperture achievable for a given taper length and acceptance angle.

**Figure 5:** (a) Plug-and-play single photon GRIN assembly setup. (b) Collected data from multiphoton coincidence measurements demonstrating single-photon behavior.

**4. Discussion**

Quantum dot nanowire sources arguably hold the greatest potential for being practical sources for field-ready quantum technologies. The ability to tune physical parameters during growth to yield superior performance metrics such as single-photon purity, brightness and adjustable numerical aperture, promises to make quantum dot nanowire sources an essential ingredients in future real-world quantum information schemes.

**5. Conclusions**

This work aims to develop and deliver quantum technologies based on the excitonic engineering and photonic design of quantum dot nanowire sources. Site-selected epitaxial growth with specialized confinement strategies for the emission of field-appropriate wavelengths in a tapered geometry that allows for a high degree of optical integration promises to make nanowire sources a key enabling resource for field-deployable next-generation quantum technologies.

**Acknowledgements**

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**References**


Highly efficient nanophotonic color router for sub-micron-pixel CMOS imagers

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Abstract

We have demonstrated novel nanophotonic color-routing structures that can efficiently split and focus different colors onto corresponding pixels of an image sensor. Direct color-separating capability without the use of absorptive filters provides each pixel with more photons of the desired wavelength, resulting in higher signal-to-noise ratios. Experimental demonstration shows a great promise for both highly efficient RGB color separation and tight focusing of sorted light into submicron pixels: we measured 3.9 and 1.9 dB improvements of YSNR under 20-lux and 700-lux illumination, respectively, over a conventional reference image sensor without distorting the color balance. The fabrication process is CMOS-compatible, promising practical realization of the highly efficient sub-micron-pixel CMOS-image sensors that are also suitable for mass production.

1. Introduction

The pixel-shrinking trend on CMOS image sensors (CISs) has been continuing, and now the pixel sizes are approaching 0.8 µm. While the pixel shrinkage offers higher pixel counts in a given area and allows thinner, more compact camera modules, the reduction in light-receiving areas causes decreased signal-to-noise ratios (SNRs) [1]. Instead of using inefficient conventional RGB color filters and microlenses, we demonstrate an alternative optical route to redistribute and focus incident light energy efficiently by color. We incorporate properly designed sub-wavelength scale photonic structures to overcome the inherently limited photon budget of the conventional approach. Color-filter materials have gradually been improved over the years to exhibit better spectral performance with higher transmission in the desired pass-bands and smaller crosstalk between adjacent pixels. However, in the conventional approach, almost two thirds of the incoming light energy is absorbed in the stop-bands of the color filters, and this remains as a fundamental limitation for CISs. To overcome this limitation, noteworthy efforts have recently been made to replace the conventional color filters with meta-photonic color routers [2-4].

However, the performance of the reported metaphotic devices fell short of the quality required for commercialization, exhibiting severe color crosstalk, poor angular response, and low SNRs due to an additional color correction process. Here, we propose a novel approach to innovate the current optical layers in CISs by integrating nanophotonic structures to manipulate incoming light efficiently and to increase quantum efficiency and color reproduction quality while maintaining angle-independent response comparable to that of typical image sensors.

2. Experiment

Our color-routing nanophotonic structures are made of transparent TiO₂ with high refractive index (n > 2.4 @ 400–700 nm). To investigate the performance, we designed and simulated the nanophotonic structures using the FDTD method (Lumerical) and obtained expected QEs shown in Figure 1(a). The simulated QEs represented by solid lines show high gains in all channels: R: 139 %, G: 163 %, B: 165 %, and B: 143 % with respect to their counterparts of the reference image sensor indicated with dashed lines. For experimental measurements, we fabricated the color-routing
nanophotonic structures directly on top of the 1.12-μm pixels of a CMOS-image sensor with the Bayer color pattern and characterized the sensor first by assessing its quantum efficiency (QE). The measured QEs of the sensor integrated with the color router are represented by the solid lines in Fig. 1(b): R: 175 %, G\(_R\): 217 %, G\(_B\): 219 %, and B: 182 %, or about 30 % more than the simulated values due to the offset signal caused by fabrication imperfections including misalignment between the color-routing nanostructures and image-sensor pixels and size variations. The measured crosstalk was also about 10% larger than the simulated result for similar reasons (Table 1). Nonetheless, the overall spectral shapes are in good agreement with the simulation results, testifying the fabricated color-routing nanophotonic structures effectively redirect and focus light by color to the assigned pixels with much improved efficiencies. To investigate YSNR and color errors, we captured the images of the 24-color checker in the studio using the reference and color-router sensors (Fig. 2). For fair comparison, we kept all the imaging conditions the same for both sensors including the use of identical camera modules and the standard scene-illumination condition D65. We have confirmed that the color-router image sensor improves YSNR by 3.9 dB and 1.9 dB under 20 lux and 700 lux, respectively, and exhibits color errors smaller than the reference image sensor (Table 2).

### 3. Conclusions

We have demonstrated color-routing nanostructures that can efficiently split and focus red, green, and blue colors onto assigned submicron pixels. The performance of the color-router imaging sensor was experimentally verified by integrating them directly onto a standard CIS whose pixel size measures 1.12 μm. The experimentally obtained images showed huge YSNR enhancement, especially in the low-light environment while exhibiting equivalent color reproduction and excellent responses under angled illumination. These results prove that the presented color-routing nanophotonic approach opens up a practical route to highly efficient sub-micron-pixel CISs for both mobile and automotive applications.

### References


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**Figure 2:** Captured images of the 24-color checker under the D65 / 700 lux illumination condition (a) reference image sensor (Bayer color array) (b) image sensor with light deflector

**Table 2: Measured YSNR (dB) and Color Error**

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Brillouin Spectroscopy in Optophononic Micropillars at 18 GHz

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Abstract

We measured the Brillouin spectrum on an elliptical optophononic micropillar resonator based on AlAs/GaAs superlattices designed to confine light and sound simultaneously. The ellipticity has associated two polarized modes used to discriminate the reflected laser and the Brillouin signal.

1. Introduction

Inelastic scattering of light by acoustic phonons has potential for the tailored generation of frequency combs, laser-line narrowing, and all-optical data storage. These applications require strong optical fields and a large overlap between the optical and acoustic modes to be efficient. The main obstacle in Brillouin scattering measurements on objects of a few µm size is stray-light rejection. This limits the accessible acoustic phonons to few tens of GHz. Maximizing the signal-to-noise ratio in a free-space Brillouin scattering measurement has already been done by introducing a spatial mode mismatch between the incoming laser beam and the optical micropillar mode [1]. In this work, we used the signal polarization to filter out the collected laser.

2. Methods and results

We designed an optophononic elliptical micropillar resonator based on AlAs/GaAs superlattices to simultaneously confine light and sound with an acoustic mode at 18 GHz (Fig. 1(a)). This results in enhanced optomechanical interactions [2,3]. Due to the pillar ellipticity, the degeneracy of horizontally (H) and vertically (V) polarized cavity mode is lifted (fig. 1(b)), leading to polarization-dependent reflection coefficient r_H and r_V. The splitting between the two optical modes depends on the ellipticity and size of the pillar.

We present a novel strategy to maximize the signal-to-noise ratio in a free-space Brillouin scattering measurement. We developed a polarization filtering technique based on the rotation of polarization induced by the elliptical micropillar. The filtering relies on a mode matching between the incoming laser beam and the optical micropillar modes. By resonantly exciting the pillar with a mode-matched beam of polarization projected on both H and V, the reflected laser and the Brillouin signal undergo a different rotation of polarization.

We measured an elliptical pillar presenting an optical mode with a Q-factor of 6000 and an optical mode splitting of ~0.1nm, as shown in Fig. 1(b). Fig. 2 presents the Brillouin spectrum obtained for the incident laser tuned at 900.17 nm and appropriately filtered out using waveplates. The laser wavelength is set so the polarization of the Brillouin signal at 18 GHz is maximally rotated compared to that of the reflected laser.

Fig 1: (a) SEM image of an elliptical micropillar with a diameter of 5x1 µm. (b) Measured cavity reflectivity for horizontally polarized (blue) and vertically polarized (red) incident light as a function of the laser-cavity detuning energy for a micropillar with major and minor axis respectively equal to 4 and 2 µm.
Fig. 2: Measured Brillouin spectrum on a micropillar with major and minor axes equal to 4 and 2 μm, respectively. The incident laser is tuned at 900.17 nm. The spectrum exhibits two peaks at 18 and 37 GHz.

3. Conclusion

We measured the Brillouin signal on elliptical micropillars with diameters of a few μm. The optophononic micropillars could be integrated into fibered and on-chip [4], can be engineered to reach the stimulated Brillouin scattering regime, and are compatible with quantum dots, making them relevant for quantum communication.

References


Plasmon dephasing and macroscopic polarization conversion in single nanoporous particles

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Abstract
Plasmon damping strongly affects their temporal and spectral behaviour and determines their ability to enhance the characteristics of metamaterials tailored to a wide range of applications, including electric-field enhancement, hot-electron injection, and sensing. Coupled and mesoscopic plasmonic systems having complex spectra generally impede damping analysis. As such, we report that polarimetric dark-field microscopy with an incident circular polarized laser is sensitive to the plasmon dephasing and also unambiguously records the change in damping induced upon adsorption of molecules. We validate the relationship with finite element analysis and experiments on gold nanoparticles and silvered nanoporous silica particles. Remarkably, after molecular adsorption, the nanostructured particles scatter with a polarization plane rotated by 90 degrees, when analyzed with a quarter-wave plate and linear polarizer together. These results offer new perspectives in molecule sensing and materials tunability for light polarization conversion at sub-microscopic scale.

1. Introduction
The excitation and radiation of plasmonic structures and nanostructures are well-known to depend on their shape and geometry, and on the polarization of the light that excites or that is detected. Plasmon-mediated fluorescence in Au nanorod [1] and photoluminescence in single Au nanowire [2] exhibit a strong dependence on polarization. Polarization is one of the key attributes of light and controlling the state of polarization leads to a variety of scientific findings and a plethora of applications [3]. Chiral metamaterials of have been designed to control or switch the polarization states of light, for example by switching the linearly polarized light from one polarization to its crossed polarization [4, 5]. Changes in the polarization state of light in plasmon-based materials are also used in a variety of molecular sensing platforms, with the well-known surface plasmon resonance (SPR) method using a scheme derived from ellipsometry to assess a change in refractive index at the sensor surface, then associated to the adsorption of the targeted molecular species or biomolecules. Porous silica and silicon stand apart thanks to their morphological structure, which includes large surface to volume ratio, adjustable porosity and pore sizes, along with low-cost fabrication and compatibility with microfabrication technologies. Using microparticles that can mix and freely circulate in liquid increases the likelihood of detection, and mobile microparticle sensors are thus especially suited in a variety of sensing schemes. Here, we have embedded Ag nanoparticles in nanoporous silica microspheres and studied the polarization of the scattered light using a dark field microscope. We observed that when the incident light is circularly polarized, the scattered light polarization is inverted for wavelengths around the plasmon resonance. Remarkably, the inversion is not seen when monolayers of dodecanethiol (DDT) or of ethylnylaniline (EA) are added into the silvered pores, making the method highly sensitive if developed as a sensing platform. We also discuss how the polarization phase relates to the observations and can be proposed to justify these new findings.

Figure 1: (a) SEM image of a nanoporous silica microparticle after silver reduction. (b) Same for a microparticle that has been cut by FIB to reveal Ag nanoparticles in the pores. (c) Darkfield spectra of single microparticles (as prepared, after addition of DDT, after addition of EA).

2. Methods and Results
Nanoporous silica microparticles (1.5 µm) were measured after thorough cleaning and after reduction of silver salt at the surface and in the nanopores [6]. Darkfield spectra were recorded using a home-made microscope based on a high NA oil immersion DF condenser (NA 1.2-1.3), a broadband white light source, a collection objective (NA 0.9), and an ACTON spectrograph. A redshift of the wavelength of the maximum scattering is measured when DDT and EA are added (Figure 1).

For polarization studies, we built a second transmission microscope using a low NA (<0.6) objective to
focus a visible monochromatic tunable laser beam onto the microparticles deposited on a glass slide and attached to a piezo scanner to record images. The collection was made by a darkfield objective (NA 0.8, with the low NA core blocked) and the scattered light was measured with a photomultiplier (PMT). A tunable quarterwave plate (QWP) was used to achieve on the sample circular polarization of the originally linear polarized incident beam, and a second QWP was introduced in the detection path so that the circular polarization is made linear again for analysis with a linear polarizer (LP) in front of the PMT. The polarization and second QWP alignment were verified in bright field before darkfield measurements.

Figure 2: (left) Polar plots of the transmitted light on a silvered nanoporous silica microparticle at 790 nm in bright field (red), darkfield (blue), and on the (depolarized) glass background (green). (right) Same after addition of EA.

In Figure 2, we show that in bright field the circular polarisation (red) remains unchanged and other data shows that this is the case for any wavelength and systems tested, as expected since most of the incident light is transmitted with little perturbation. Our main finding is that the scattered light measured in darkfield (blue) has a polarization that strongly depends on the wavelength and on the Ag surface (ie, with or without the addition of EA and DDT). We found this inversion of the polarisation remarkable given that the system is spherical and its porosity is amorphous. We discuss theoretical evidence, based on COMSOL Multiphysics, that the changes in polarisation are likely due to variations in the polarisation phase in the specimen and on the porous nature of the microspheres.

3. Conclusions

As an important property of plasmonic material, the polarization of the scattered light in nanoporous SiO2 microspheres coated with Ag nanoparticles was investigated by darkfield micro-spectroscopy. Illuminating the microparticles with circularly polarized lasers lead to an inversion of polarization that is further tuned by the addition of a monolayer of DDT or EA. We propose that these particles and polarization scheme can be used for sensitive sensing of molecule adsorption at single particle level.

Acknowledgements

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References

Experimental Probes of Thermal Transport and Lattice Stability of Important Optoelectronic Semiconductor Nanomaterials

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Abstract

We performed transient X-ray diffraction experiments on semiconductor nanocrystals and lead halide perovskites. Bragg peak shifts relate heating and peak amplitude reduction confers lattice disordering. II-VI nanoparticles melt upon absorption of \( \sim 0.89 \) excitations/nm\(^3\). Certain perovskites are found to undergo solid-solid phase transitions prior to disordering. Diffraction intensity recovery kinetics occur over hundreds of picoseconds with slower recoveries for larger particles. These findings highlight questions of physical stability of advanced materials and related electronic impacts in high intensity excitation applications.

1. Introduction

While many semiconductor material applications such as photoluminescent labels, light-emitting diodes (LEDs), and solar absorbers employ low-intensity generation of electron-hole pairs (often referred to as ‘excitons’ regardless of binding energy owing to spatial confinement within the particle), applications such as optical amplifiers and high brightness LEDs can excite multiple excitons or experience very high frequency excitation. Biexciton lifetimes in nanocrystals (NCs) scale with particle volume for a wide range of compositions, while triexcitons and higher numbers of excitations per NC decay progressively faster according to the number of carriers present in the particle. Thermal energy is transferred to the NC lattice upon both intraband cooling of each photogenerated exciton and multie excitonic Auger-recombination that, given the reduced particle volume and lower equilibrium melting temperature relative to the bulk composition, raises questions regarding the stability of the particle lattice. Similarly, organic-inorganic lead halide perovskites experience unusual thermalization processes that raise questions as to the role of thermal energy from aspects such as photogenerated carrier lifetime to material stability against degradation.

We performed transient x-ray diffraction experiments using Beamline 11-ID-D at the Advanced Photon Source (Argonne National Laboratory). Typically, a reservoir of semiconductor NCs dispersed in alkane was continuously flowed as a free jet into an air-free interaction region, which assured measurement of fresh, unperturbed material with each laser pulse. Pump pulses of 3.1 eV photon energy from a 100 fs Ti:sapphire laser were attenuated and focused to achieve the desired fluence. After a controlled time delay, 11.7 keV X-ray pulses (79 ps fwhm) were directed into the jet, and the resulting 2D diffraction pattern was collected on a time-gated Pilatus 2M, which was then radially integrated.

Figure 1: a) Static x-ray diffraction of a jet of CdSe nanocrystals. b) Transient x-ray diffraction at 80ps time delay for an average number of absorbed photons per excited nanocrystal \(<N>\) as indicated shows transient disordering.
2. Discussion

Measurement methods such as transient x-ray diffraction help to convey the importance of lattice dynamics and derived electronic impacts of such motions on the performance of semiconductor materials. For nanocrystals as well as perovskite semiconductors, diffraction peak shifting as well as peak loss relate lattice heating and disordering directly. In nanocrystals, disordering is observed for a particular density of excitons, in some disagreement with equilibrium expectation of suppressed melting points for smaller particles. Recovery of crystalline diffraction domains scales with particle size and reflects thermal outflow from the particle to the surroundings in a diffusion-limited regime. Perovskites of CsPbBr$_3$ show disappearance of orthorhombic crystal lattice reflections with maintenance of higher symmetry lattice planes, which is consistent with solid-solid phase transitions. Such behavior relates that this perovskite composition can be influenced significantly in higher excitation density scenarios.

Figure 2: Transient disordering of semiconductor nanocrystals of CdSe for different indicated particle sizes as a function of absorbed average number of photons, $<N>$.

3. Conclusions

We showed via direct probes such as lattice expansion and disordering owing to thermal energy deposited from effects such as Auger heating and intraband relaxation, that advanced semiconductor materials heat substantially and can lose crystalline order. Recovery of the materials as followed by crystalline order and lattice contraction is limited by diffusive behavior that is made complex via ligands on particle surface.

4. Acknowledgements

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5. References


Integrated nonlinear photonics in AlGaAs-on-insulator devices

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Abstract

The heterogeneous integration of AlGaAs-on-insulator (AlGaAs-OI) has proven to be a powerful material platform for nonlinear optics. This talk will explore how chip-scale bonding and transfer printing techniques can be used for the fabrication of integrated photonic chips for highly efficient second and third order non-linear interactions. Examples to be presented will include devices for second harmonic, super-continuum and four-wave missing generation, as well as vertical geometries to engineer the interaction between different spatial modes.
Wavefront Control of Light Emission from Halide Perovskite Metamaterials

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Abstract

We propose an integrated perovskite metamaterial that enables arbitrary wavefront control of the light emitted from halide perovskites. By incorporating dielectric metasurfaces and a Bragg cavity, the CH₃NH₃PbI₃ (MAPbI₃) halide perovskite metamaterial experimentally shows directional light emission.

1. Introduction

Halide perovskites (MAPbX₃, where MA = CH₃NH₃⁺, X = Cl, Br, or I) have attracted tremendous attention for applications in photovoltaics and optoelectronics due to their low-cost fabrication, long carrier diffusion length, low defect density, and controllable bandgaps [1,2]. Light emission from halide perovskite has been utilized in high efficiency light-emitting diodes and lasers, thanks to their strong optical gain and high photoluminescence quantum yield [3]. However, full control of perovskite light emission pattern has not yet been explored, which hindered their applications and integrations in beam steering, free-space optical communications, and light detection and ranging. Very recently, direction emission from perovskite nanocrystals by 3D lenses has been demonstrated [4]. However, the method cannot be generalized for arbitrary wavefront control of perovskite light emission, nor can it be easily integrated into perovskite-based devices. In this work, for the first time, we demonstrate arbitrary light emission wavefront control from perovskite metamaterials with a designed directional emission profile.

Figure 1: In the perovskite directional emitter, a MAPbI₃ thin film is sandwiched between a TiO₂/SiO₂ Bragg reflector and thin Ag mirror, with a silicon metasurface on top. Additional SiO₂ layers prevent quenching effects and serve as etching stop layer in fabrication, while Ge layers promote adhesion between layers.

2. Design and Fabrication

The perovskite metamaterial directional emitter consists of a MAPbI₃ layer sandwiched in between a Bragg dielectric multilayer and a thin silver layer (Figure 1). The Bragg layer consists of 5 pairs of alternating TiO₂ and SiO₂ layers, which yield a 90% reflection at the light emission wavelength of MAPbI₃ (770 nm). Combining with a thin Ag layer, a Bragg cavity is formed to improve the spatial coherence of MAPbI₃ light emission [5].

Figure 2: Transmission and phase shift of silicon cylinders with varying diameters. (Inset) Unit cell of silicon metasurface, with P = 330 nm, H = 325 nm, and D is varied to acquire 2π phase shift.

Ultrathin metasurfaces, consisted of sub-wavelength antennas, are capable of arbitrarily and precisely controlling the wavefront of transmitted or reflected light [6-8]. A metasurface with cylindrical silicon posts (Figure 2, inset) is separately designed to have uniform period and height. By varying the diameters of cylinders, 2π phase shift is achieved at emission wavelength with high transmission (Figure 2). By designing 6 unit cells in a metasurface single super-cell, the directional emitter is designed to achieve 23° angled emission, as shown in the simulated far-field emission pattern in Figure 3.

The device fabrication starts with electron-beam deposition of TiO₂/SiO₂ layers. A MAPbI₃ thin film of 600 nm thick is then spin-coated on the multilayers. Ag and Si thin films are subsequently deposited on top of MAPbI₃ by electron-beam deposition. The metasurface is then patterned using electron-beam lithography with ZEP-520A electron-beam resist. After developing, e-beam resist serves as an etch mask to transfer the metasurface pattern by dry etching.
3. Measurements

The optical characterization is performed with a momentum-space measurement setup. Photoluminescence from MAPbI$_3$ is observed with a center wavelength of 770 nm (Figure 4). Without any patterns, the measured momentum space image of the emitted light at 770 nm shows a non-directional emission (Figure 5, top). In comparison, with the presence of the metasurface, directional emission at 23° ($k_x/k_0 = -0.39$) is achieved, as shown in the momentum space image in Figure 5, bottom. The emission pattern agrees well with the simulated far-field pattern (Figure 3), confirming the design principle of the perovskite metamaterial directional emitter.

4. Conclusion

We demonstrated a halide perovskite metamaterial that is capable for controlling perovskite light emission wavefront. Directional emission from perovskite metamaterial is experimentally demonstrated and similar systems can be used for perovskite orbital angular momentum generator, self-focusing perovskite lens, and non-diffracting laser beam. Direct wavefront control using the perovskite metasurfaces is important applications of perovskites in light ranging, optical sensing and communications, high efficiency lighting, and navigation.

References

Sparse Array as Metamaterial for Higher-Order Modes Suppression in an Accelerator Cavity

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Abstract

A metamaterial formed by sparsely populated array of metallic rods exhibiting photonic bandgap (PBG) properties is employed to fill a cavity resonator for future particle accelerator applications. The PBG characteristic suppresses the undesirable higher-order modes (HOMs) while supporting the accelerating TM₀₁-like mode to maintain high beam quality. Beginning with an array on a triangular lattice, certain lattice points are depopulated in the procedure to optimize the bandgap characteristic for improvement of HOMs suppression. The optimization process leads to a star-shape array. It is further refined by selective lattice point dislocation to adjust the input impedance of the cavity resonator. The cavity-waveguide assembly was fabricated with copper and cold tested for resonance characteristics. A return loss of over 20 dB at the designed resonance frequency of 11.41 GHz was measured. A bead pull experiment was performed to confirm the uniformity of the field along the axis of the cavity resonator.

Keywords— Metamaterial, photonic band gap, cavity resonator, particle accelerator, impedance matching

1. Introduction

Photonic bandgap (PBG) structures in the form of metallic or dielectric rods on a two-dimensional lattice have received considerable interest for future accelerator applications in the suppression of higher-order modes (HOM) wakefields without affecting the operating mode. PBG also enables oversized accelerating structures to be employed, which are favorable for implementing accelerators driven by higher frequency microwave sources. The PBG cavity is often formed by removal of a rod at the center while additional rods are withdrawn or removed to achieve optimal input coupling to the RF source [1-4]. In this paper, an account of the effort in the optimization of a PBG structure for HOMs suppression is described. Starting with a triangular lattice of metallic rods placed inside a cylindrical cavity, the elements at selected locations were removed or adjusted to achieve HOMs suppression and impedance matching. The optimized design was fabricated and further tuned for improved performance.

2. Optimization of PBG Array in Cavity

A PBG periodic lattice prevents propagation of electromagnetic waves at certain frequencies through the lattice. A rejection band is created which serves to confine and localize the desired mode, and the rest of the lattice causes the field to decay exponentially [6-8] in the radial direction shown in Figure 1. Thus, there is no necessity to have a large array of the PBG lattice. Three rows of metal rods surrounded by a cylindrical metal wall are sufficient to confine the desired TM₀₁-like mode in the beam region.

Figure 1: The electric field pattern of the TM₀₁-like mode.

As there is a metal wall surrounding the periphery of the resonator, it will confine higher-order modes such as the TM₁₁-like mode inside the PBG lattice. This TM₁₁-like mode contains a transverse component, which affects the emittance of the beam. However, if the electric field of such modes is kept away from the central region, there will be negligible adverse effects on the beam. In order to verify the mode filtering properties of the PBG cavity mode confinement and HOM suppression, it is necessary to feed power into the inner part, requiring some of the rods to be removed [9]. This also increases the nonmetallic volume of the cavity, which may cause either eigenmode frequency shift or new modes introduced, as shown in Figure 2.

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Based on the above observation, a PBG cavity resonator with a star shape array of metallic rod loading was designed to provide high field intensity in the center beam pipe region while maintaining the target resonance frequency of 11.4 GHz. Non-periodic lattice structures [10-13] could avoid the inherently poor damping characteristics found in a periodic lattice cavity. A non-periodic lattice PBG can be accomplished by shifting the lattice points of the metal rods at each layer symmetrically, guided by electromagnetic simulation tool CST Microwave Studio, to give optimal performance in field confinement. The PBG cavity structure resulting from the optimization routine is shown in Figure 3 (left). A color plot of the simulated electric field intensity of the TM\textsubscript{01}-like mode is shown in Figure 3 (right). Coupling of microwave power into and out of the cavity is accomplished by joining the side wall to two WR-90 rectangular waveguides with full opening of the waveguide cross section. The PBG cavity with the waveguide sections were optimized as a unit for maximum input return loss and high transmission in the final design iteration. A photograph of the cavity-waveguide assembly made with copper is shown in Figure 4.

Figure 2: Modes at lower frequencies were introduced by the presence of empty volume.

Figure 3: (left) Rod locations in an optimized PBG cavity with second and third layer rods dislocated from the original triangular lattice. Original location shown by dotted circles, (right) simulated electrical field pattern of the TM\textsubscript{01}-like mode in the PBG cavity.

Figure 4: PBG cavity with coupling waveguide integrated.

3. Measurement Results

Reflection and transmission characteristics of the PBG cavity were measured using an Agilent E8362B network analyzer. The input matching exhibited by the structure as manufactured had a return loss of 6 dB ($S_{11} = -6$ dB) due to implementation tolerance. Upon fine tuning with a slide-screw tuner to reduce the residual mismatch, a return loss of 24 dB was measured for the TM\textsubscript{01} -like mode at 11.41 GHz. The entire structure being measured is shown in Figure 5. A one port measurement of $S_{11}$ is sufficient to characterize its resonance and coupling conditions. The trajectory of $S_{11}$ on a Smith Chart over the frequency range of 11.37 to 11.47 GHz in the vicinity of the TM\textsubscript{01}-like mode resonance is shown in Figure 6.

Figure 5: Set up of cavity resonator assembly for return loss measurement.

It can be seen in Figure 7 that the measurement result has a lower reflection coefficient than that of the theoretical design. This is a result of the assumption of perfect electric conductor for the material of PBG structure in the simulation, while the actual implementation employed copper, which has a finite conductivity, hence giving rise to additional power absorption in the actual measurement. Moreover, it is necessary to check if any HOM resonates in the cavity in a wide frequency range. A number of HOMs with frequencies over 12GHz were identified by the $S_{11}$ measurement as shown in Figure 8, with simulations of the field patterns of these HOMs inserted. It reveals that none of
these HOMs would affect the accelerating TM$_{01}$-like resonant mode in the center of the cavity.

Figure 6: Smith chart trajectory of $S_{11}$ of the cavity in the vicinity of the TM$_{01}$-like resonant mode.

Figure 7: Frequency sweep of the return loss of the PBG cavity resonator.

Figure 8: TM$_{01}$-like mode and HOMs appear in a wide frequency range. The appeared HOMs would not affect the eigenmode in the center of the cavity.

A bead-pull experiment was performed to ascertain that the field was uniform along the central axis of the cavity. The frequency shift is proportional to the square of the electric field magnitude at the perturbation point [14, 15, 16]. A bead made of conductive ink was employed. By tracking the shift in the resonance frequency revealed in the reflection coefficient as shown in Figure 6, the profile of the field intensity along the path of the bead can be calculated, as displayed in Figure 10. As the cavity length is 12.04 mm, through the bead pull result, it is verified that the resonant mode is well confined within the cavity.

Figure 9: The eigenmode frequency shift due to the motion of the bead in the cavity.

Figure 10: Square of electric field intensity calculated in arbitrary unit from the frequency shift data in Figure 9.

4. Summary

Beginning with a triangular lattice populated with metallic rods as a metamaterial with PBG characteristic, the array was optimized for HOMs suppression when placed inside a cavity resonator for future accelerator applications. The resultant star-shape array was arrived at after removal and dislocation of certain elements to accomplish HOMs suppression and impedance matching with waveguide excitation. Cold test of a cavity assembly fabricated with copper validated the design, showing a measured return loss of over 20 dB for the TM$_{01}$-like mode at 11.41 GHz with confinement and HOMs elimination at the center location. Performance of the PBG cavity renders it an efficient candidate for the construction of a multi-cell resonant
structure for the next generation of particle accelerator with advancement in beam quality.

References

Phase change material based nanophotonics: multiphysics modelling

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Abstract

Phase change materials are materials in which phase transitions can be induced quickly and reversibly, resulting in pronounced changes in materials’ physical properties. By changing a phase of the material near a localized optical element, being a part of an electronic or optoelectronic component or a functional element of a metamaterial, it is possible to realize reconfigurable, time dependent and (re)programmable functionality with applications in neuromorphic computing, high-frequency electronics, optoelectronics and electromagnetic metamaterials. Phase change materials can be switched non-volatilely between amorphous and crystalline phases by annealing and short electrical or optical pulses. The deposited energy is typically strongly inhomogeneous and the resulting phase transition is spatially non-uniform. The drastic change of the material properties during the phase transition leads to time-dependent changes in the absorption rate and heat conduction near the switched element. These necessitate a self-consistent treatment of electromagnetic, thermal and phase transition processes. In this presentation we report on recent developments and applications of a multiphysics description of phase change material based nanophotonic systems.
Advanced passive and active metasurfaces and zero-index optics
A new approach to meter-scale and durable all-dielectric meta-optics: gains and challenges

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Abstract

We present an alternative approach to dielectric meta-surfaces based on resonant elements which has far less limitations on scalability and durability. The process is based on laser raster-scan of a thin metal film on a glass, followed by dry-etching and removal of the metal mask. Since the air-glass volumetric ratio mixing approach is limited by the depth of the layer, we have developed approaches to “boost” the attainable phase response, to be discussed here.

1. Discussion

A critical enabling step in the advancement of meta-optics into commercial application space is evolving the fabrication process to be scalable and the end-result structure to be environmentally stable. The commonly used approach for designing a dielectric meta-surface is based on resonant elements, which has been perfected to give astonishing control over the optical response of the elements. However, this approach also limits both the scalability and the durability of the meta-surface, due to the high accuracy control required for the nano-features requiring utilization of high-resolution lithography.

Here we will present an alternative approach, which has inherently less limitations on scalability, and furthermore has inherent high environmental stability. However, the main challenge for this approach becomes enhancing the magnitude of the attainable phase response.

The process we recently presented \cite{1}, utilizes a laser induced de-wetting of Au thin film on silica substrate, followed by dry etching through the nanoparticles mask and removal of the residual Au, to result in a glass-engraved meta-optics. Since the masking fill-factor was found to monotonically depend on the local laser induced heating, a laser raster scan gives the means for controlling the end-result meta-optics local effective index. The process is relatively simple, scalable and results in a relatively environmentally stable structure consisting predominantly of fused silica.

Yet, the meta-surface consists of randomly distributed nano-features, determining locally the effective index by means of Bruggeman mixing formula of the air-glass volumetric ratio. While that presents opportunities in terms of into-the-layer graded-index profile, the amount of phase change is limited by the depth of the layer. We have demonstrated the optical

index pattern printing, durability, and developed approaches to “boost” the attainable phase response.

In this talk we will discuss the gains and challenges of this promising approach, show modeling as well as fabricated and measured structures, and demonstrate its level of durability. We will also discuss the methods to enhance the linear and nonlinear optical properties of these structures.

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References

Metasurface enhanced high-sensitive IR spectroscopy

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Abstract

Metasurfaces consist of metal-insulator-metal structure were developed for a versatile platform of high-sensitive IR spectroscopy. A device with nano-fluidic channel allows the introduction and precise control of number of analyte molecules into the intense electromagnetic field of metamaterials, resulting in the improvement of sensitivity up to 2 orders compared to state-of-the-art plasmonic enhanced IR spectrosopies. High sensitive gas spectroscopy has also demonstrated by the use of vertically aligned MIM metasurface device. These devices provide the capability of quantitative measurement of molecules.

1. Introduction

Label-free detections of molecules are highly demanded in bioanalysis applications. IR spectroscopy is one of the label-free techniques and gives us chemical information of molecules from spectra. However, application of IR spectroscopy in bioanalysis is still limited due to its low sensitivity.

Recent advances in plasmonic metamaterials enable us to create unprecedented optical materials and perfect absorptive material surfaces within a certain frequency range were demonstrated. Since the metamaterial absorber offers a unique surface condition with tailored absorption properties as well as strong plasmonic enhancement, a wide variety of potential applications such as high-efficiency thermal emitter, high-sensitive bio-chemical sensing, and so on have been proposed. In this paper, we propose metasurface devices that improve the sensitivity of IR absorption spectroscopy.

2. Metasurface for background suppressed IR spectroscopy

We demonstrate background-suppressed resonant SEIRA of organic molecules adsorbed on an IR absorber metasurface [1].

Figure 1(a) shows a unit cell cross-section of a multilayered IR absorber metasurface consisting of a 50-nm Au micro-ribbon on a thick Au film separated by a 30-nm MgF₂ gap layer forming metal-insulator-metal (MIM) structure [1]. The width (w) and unit cell dimension (Λ) were 1.5 µm and 3 µm, respectively. The surface structure was purposely designed to exhibit an anomalous IR absorption at ~3000 cm⁻¹, which spectrally overlapped with symmetric/anti-symmetric C-H stretching vibrational modes. This structure was fabricated using a standard photo-lithography and lift-off processes. Figures 1(b) shows a photograph of the fabricated metamaterial absorber with a total area of 26 × 26 mm² and its SEM image.

Figure 2 shows the measured reflection spectrum of the 16-MHDA SAM on a bare Au surface at incident angle of 40°. Using the SAM packing density of 21.4 Å²/molecule, we estimated the amount of the molecules within the IR beam spot to be ~1.8 attomoles (1.8 × 10⁻¹⁸ mole).
3. MIM metasurface and nanofluidic hybrid device for higher sensitivity

To full utilize plasmonic field enhancement property of MIM metasurface, positioning analyte molecules exactly at the hot-spots is crucial. In order to introduce the analyte molecules to the hot-spot regions, we introduced the nanofluidic channel onto the MIM metasurface [2].

The structure of proposed device consists of metal square-disks array and metal mirror separated by a nanofluidic channel as shown in Figure 3. The interaction between top square nanostructure and bottom mirror forms the quadrupole resonance, and it suppresses the light reflection from the device. When the molecule whose absorption is overlapped with this mode is introduced, strong interaction between molecules and metamaterials is excited and it creates the reflection light within the absorption band of the metamaterial.

Figure 4 shows an experimental result when octadecane (C_{18}H_{38})/CCl_{4} solution was introduced into the nanofluidic channel. Using this device, its sensitivity reached at molecule density of ~10^{-4} molecules/Å², which is improved by 2 orders compared to reported plasmonic induced IR detection methods. We also succeeded in the quantitative determination of absolute number of molecules by precise fluidic operation.

Moreover, the device allows the confinement of both molecules and plasmonic energy inside the nanocavities. We confirmed that strong H-bonded network water confined in 10-100 nm regime existed when the pure water was introduced into the nanofluidic channel of the device. Our method can provide the capability for in-situ probing molecular dynamics and chemical reactions in the nanomater scale space [3].

4. Vertical MIM metasurface for gas sensing

Signal strength from molecules also depends on the density of the hot spots. In order to increase the density of hot spots, we designed and fabricated the vertically aligned MIM (v-MIM) structure with a nano-gap of 25 nm channel which enabled the delivery of small molecules into hot-spot region [4]. This metamaterial was applied to carbon dioxide and butane detection designing to exhibit a resonance at 4033 cm^{-1} and 2945 cm^{-1} which spectral overlap with the C=O and -CH₂ vibration mode, respectively. Because of small footprint of v-MIM structure, density of the MIM structure is substantially increased and its sensing performance was also improved.

Figure 5 v-MIM structure.

Acknowledgements

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References

Metaphotonic Computational Image Sensors

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Abstract

Conventional imaging systems are usually composed of bulky glass optics, and while they work well for many applications, they offer little functionality in applications where system size is a constraint. Optical metasurfaces provide a thin and light-weight alternative to conventional bulky optical elements by manipulating light scattering via resonant nanostructures. The inherent diffractive nature of metalenses induces severe chromatic aberrations when imaging under broadband illumination, which limits their potential applications where multi-color information is important. In this work, we present an alternative metalens plus computational design where the point spread function is engineered to be spectrally invariant to reduce chromatic aberrations and enables computational reconstruction of a measurement using a single digital filter. The created lenses have a f-number of unity and generate in-focus images under white-light illumination.

1. Introduction

Conventional optical imaging systems consist of glass optical elements that produce high-quality images with minimal aberrations. Although these systems create high-quality images, their size and weight limit their use for a variety of applications requiring compact image sensors (such as in-situ imaging of biological samples). One route to reducing an imaging system’s size and weight is via metasurface based optics [1,2]. In this approach, a surface is patterned with resonant optical antennas that manipulate the electromagnetic wavefront to scatter light in a desired fashion. Metasurfaces have already enabled flat implementations of lenses, vortex generators, axicons, and blazed gratings. This approach works well to create monochromatic lenses with wavelength-scale thickness, which enables extremely thin and lightweight systems to be built. Another approach to simplify optical systems is via computational imaging. Computational imaging combines a physical optical system with a software post-processing algorithm to form a better overall image. This approach has been shown useful in creating much simpler and cheaper optical systems that produce comparable image quality to state-of-the-art cameras.

Due to the diffractive nature of metasurfaces, designing a metasurface completely free of chromatic aberrations remains an outstanding problem in the community. The chromatic aberrations in meta-surfaces arise from the local resonant behavior of sub-wavelength scatterers, as well as from phase wrapping discontinuities arising from the spatial arrangement of scatterers. The chromatic aberrations are particularly harmful when designing lenses to be used under white-light illumination as they manifest themselves as color-dependent blurring in the formed images. In this paper, we review our recent work \cite{3,4} and discuss future research directions on a system comprising of optical hardware and a post-deconvolution algorithm to mitigate the aberrations induced by a metalens.

2. Computational Imaging

The imaging system poses a problem in the matrix form of \( f=Kx+n \), where an image \( x \) has been blurred by a matrix \( K \) and corrupted by noise \( n \) to produce a captured image \( f \). The kernel \( K \) can be formed by measuring the PSF of the system. There is a variety of methods for estimating \( x \) with a known \( K \) such as the linear Wiener filter or regularized optimization-based methods. In this work, we chose Wiener deconvolution to reconstruct the image due to its low computational complexity and comparable performance to more advanced deconvolution methods.

2.1. Performance Characterization

To demonstrate the imaging capability of the system, we illuminated patterns on standard printer paper at object distances on the order of a few centimeters. We first characterized the system by using three narrow-band (30 nm) LEDs to illuminate the 1951 Air Force resolution pattern (figure 1A) and a picture of Mona Lisa (figure 1B) separately. Figures 1C and 1F show the performance of the singlet lens. At the green wavelength, the single lens shows an in-focus image with little blurring, but under blue and red LED illumination, the images are severely blurred. Figures 1D and 1G show the performance of the EDOF lens without a computational filter. The images appear to be blurry across all 3 different illumination wavelengths, however the blur looks to be uniform across the wavelengths. Figures 1E and 1H show the results of the resultant image by combining the EDOF lens and Wiener deconvolution. The images are in-
focus at all 3 different wavelengths and show a significant performance improvement over the singlet lens. To quantify the performance improvement of the EDOF plus deconvolution lens, we calculated the structural similarity between the images captured with the red LED to the images captured by the blue LED for the case of the Air Force resolution test chart. We found that the SSIM between the two wavelengths for the singlet lens was 0.748, while for the EDOF plus filter system the SSIM was 0.956, which is a substantial 0.209 improvement.

Figure 1: Evaluation of system performance at narrow-band LED illumination. A is the 1951 Air Force resolution pattern, B is a picture of Mona Lisa. C and F are the images captured using the singlet lens. D and G are the images captured with the EDOF lens without deconvolution. E and H are EDOF lens images with deconvolution. Scale bars are 20 µm.

3. Discussion

In our future work we plan to explore optical elements with alternative phase functions that can produce an EDOF. The outstanding problem with using the cubic phase we presented in this paper is the rotational asymmetry of the point spread function which results in horizontal and vertical post-deconvolution defects in the resulting image. Some possible lens phase equations to explore that produce a rotationally symmetric PSF are the log-asphere function given by:

$$\varphi(r) = -\frac{2\pi}{\lambda} \left( \sqrt{r^2 - z_0^2} - z_0 \right)$$

$$- \frac{\pi}{\lambda y} \left[ \log \left( \frac{2y}{\sqrt{r^2 + (s_1 + y r^2)^2} + (s_2 + y r^2)} + 1 \right) \right]$$

where the parameter $y$ is given by $(s_1 - s_2)/R^2$, where $s_1$ and $s_2$ correspond to the extent of the depth of field, $R$ corresponds to the lens radius, and $z_0$ is the focal length of the lens. Another approach to developing a rotationally symmetric point spread function is by combining a lens phase with an axicon which is specialized lens that has a conical surface, with a phase function given by:

$$\varphi(x, y) = \frac{2\pi}{\lambda} \left( \sqrt{x^2 + y^2 + f^2} - f \right) + \frac{2\pi}{\lambda} \left( \sqrt{x^2 + y^2} \right) \sin \beta$$

where $x$ and $y$ are the lens coordinates, and $\beta$ is the axicon angle. By finding a proper value of the axicon angle, an EDOF can be produced. Finally, we can explore other cubic phase functions to generate an EDOF. The generalized cubic phase mask (GCPM) given by:

$$\varphi(x, y) = \alpha \left( x^3 + y^3 \right) + \beta \left( x^2 y + xy^2 \right)$$

and the sinusoidal cubic phase mask (SCPM) can be given by:

$$\varphi(x, y) = \alpha \left( x^3 + y^3 \right) + \beta \left( \sin(\omega x) + \sin(\omega y) \right)$$

where the term $\alpha$ represents the strength of the CPM, and $\beta$ represents the deviation of the mask from a CPM. These parameters must be tuned in order to obtain an EDOF mask.

4. Conclusions

In this work, we have shown, what is to the best of our knowledge, the first realization of full-color imaging under direct white light using a metasurface and computational imaging. The reported system combines computational imaging, and an EDOF metasurface to produce in-focus images across the entire visible spectrum with minimal chromatic aberrations. Although the system is composed of a digital filter, delaying the image formation, for many photography and video applications, this does not pose an issue as any images can be saved and post-processed offline. Furthermore, for real time imaging applications the system can be implemented on FPGAs and GPUs, as the filter only relies on the $O(N \log N)$ fast Fourier Transform algorithm. With the full visible spectrum focusing capabilities, EDOF lenses are a promising route for realizing next generation lenses with reduced size and weight, making them well suited for microscopy, hyperspectral imaging, and ultrathin cameras.

Acknowledgements

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References


Electrically Tunable Metasurface for Complex Amplitude Modulation

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Abstract

Tunable plasmonic modes offered by graphene provide new opportunities to create electro-optically active devices with novel characteristics that have thus far been impossible to be realized by using conventional media. In this talk, we introduce dynamic complex amplitude modulation in graphene-based metasurfaces [1].

The use of reconfigurable metasurfaces to dynamically control the complex amplitude modulation of scattered light has stimulated the interest of the research community. Despite an extensive cumulative body of knowledge in metasurfaces, insights and observations for the most intriguing possibilities have remained elusive due to the lack of design methodology. All proposed designs thus far can only control the optical phase over a fraction of a wavelength, and, furthermore, they are highly inefficient, and couple the phase and amplitude of the scattered light. In short, the current strategies offer very low prospects of creating a transformative optical device. This fundamental problem poses severe performance limitations – particularly for applications relying on accurate spatiotemporal complex field modulation, which includes dynamic holography, high-resolution imaging, optical tweezing, and optical information processing.

In this talk, we present a new strategy for dynamically controlling the local complex amplitude of light. We devise “metamolecules” consisting of a pair of subwavelength graphene plasmonic metaatoms. Independent tuning of the two metaatoms secures the complete control of both amplitude and phase of light. Our proposed metasurface allows for 2π phase shift as well as large amplitude modulation including perfect absorption. The capabilities of the proposed metasurface were proven by demonstrating active beam steering and holographic wavefront reconstruction with an unprecedented figure-of-merit. Our proposed metamolecule represents a conceptual advancement to metasurface design, allowing for complete amplitude and phase control of light, and should find its application in active thermal engineering and real-time hologram systems beyond the mid-infrared.

References

Bound states in the continuum in metasurfaces with dipolar meta-atoms

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Abstract
We explore the emergence of bound states in the continuum in metasurfaces consisting of dipolar meta-atoms. To this end, we derive a coupled electric and magnetic dipole theoretical formulation to describe the optical properties of a periodic array consisting of one/several electric/magnetic dipoles per unit cell. We exploit this general formulation to investigate robust symmetry-protected bound states in the continuum through different mechanisms in various kinds of arrays of interest throughout the electromagnetic spectrum: high-refractive-index disks in the GHz; metallic rod dimers in the THz; and silicon nanodisks in the visible.

1. Introduction
Bound states in the continuum (BICs) have attracted much interest lately in photonics for their (theoretically) infinite Q factor. These states are resonant modes that, despite lying in the continuum, cannot couple to any radiation channel [1]. In order to trap light in such nearly-zero-linewidth electromagnetic modes, a common approach is to exploit metasurfaces [2]: namely, planar periodic arrays with periodicity such that only the specular channels are allowed in the spectral range of interest. The strategy is to suppress those outgoing specular channels by tuning the parameters of the system in various manners, leading to symmetry-protected BICs.

2. Theory & Results
In order to explore BICs in metasurfaces, we have developed a coupled electric (ED) and magnetic dipole (MD) formulation for infinite planar arrays where the electric and magnetic polarizabilities are given by the meta-atom response, which may include various dipoles at different positions within the unit cell [3-5]. In this manner, we can theoretically calculate the reflection from and transmission through a planar periodic array of electric and magnetic dipoles.

We have thus investigated various configurations amenable to fabrication throughout the electromagnetic spectrum:

2.1. High-refractive-index disk array in the GHz regime
An array of single perpendicular MDs is shown to exhibit a so-called Brewster BIC at normal incidence, which evolves into a quasi-BIC at oblique incidence with a rich phenomenology as the (non-degenerate) MD is tilted. This has been in turn verified through a high-refractive-index (s~80) disk metasurface (see Fig. 1a) in the GHz domain in turn provides clear experimental evidence of such Brewster BICs and quasi-BICs [4].

(a) (b)

Figure 1: Schematics of the metasurface configurations studied here: (a) Disk arrays and (b) rod dimer arrays.

2.2. Au rod dimer array in the THz regime
A dipole-dimer array has been shown to yield a BIC at normal incidence as the dipole detuning parameter vanishes. In this case, the physical mechanism is in-plane inversion symmetry protection. This has been experimentally verified through a Au-rod dimer metasurface (see Fig. 1b) in the THz domain [5]; by varying the size of each dimer rod, resembling detuned in-plane dipole meta-atoms, the BIC condition is approached as the detuning parameter tends to vanish (for identical rods), so that inversion symmetry is recovered.

2.3. Si disk array in the visible
Finally, a mechanism similar to that for HRI disk meta-atoms mentioned above (see Fig. 1a) is extrapolated to the optical domain. Since the available materials in the visible and near-IR show much lower refractive index contrasts, ED and MD resonances tend to overlap. By using low aspect ratio disks, we observe that the lowest-order MD resonance appears
spectrally separated from the other in-plane/out-of-plane electric/magnetic dipole resonances. Thereby, we demonstrate experimentally the emergence of symmetry-protected BIC in the optical domain in an array of polycrystalline Si disks [6].

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References

Nonlinear Doping of Epsilon-Near-Zero Media

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Abstract

We theoretically explore the possibility of obtaining enhanced magnetic nonlinearity by doping a linear epsilon-near-zero (ENZ) host with a nonlinear dielectric inclusion. As an application of this concept, we exploit the enhanced nonlinearity in the context of a nonlinear absorber where we deploy a nonlinear doped ENZ slab as the spacer layer in a Salisbury screen. In addition to the enhanced nonlinearity, such absorbers are shown to exhibit highly tunable characteristics, such as bandwidth control.

1. Introduction

Epsilon-near-zero (ENZ) media have been extensively studied since the recently renewed interest in metamaterials. The exotic electromagnetic properties exhibited by such structures have rendered them suitable for a broad range of applications[1]. For instance, recent investigations have illustrated the huge enhancement of nonlinear optical effects in ENZ media[2].

Here, we present an alternative approach for obtaining enhanced nonlinear responses from ENZ structures. Rather than deploying an ENZ medium with a strongly nonlinear response, we illustrate the prospect of achieving a highly nonlinear effective medium by doping a linear ENZ host with one or more nonlinear dielectric inclusions[3]. By engineering the size, geometry, and permittivity of such inclusions with relatively weak electric nonlinearity, the resulting nonlinear doped ENZ exhibits an effective near-zero permittivity, \( \varepsilon_{\text{eff}} \approx 0 \), while exhibiting a modified effective permeability \( \mu_{\text{eff}} \neq 1 \) where \( \mu_{\text{eff}} \) is found by finding the magnetic flux through the doped ENZ by integrating the magnetic field distributions over each dopant[5].

One of the powerful features of this concept, coined photonic doping, is its applicability to an ENZ host with an arbitrary geometry doped with an arbitrary number of inclusions, dopant geometries and electrical sizes, as depicted in Fig. 1. Moreover, the effective permittivity and permeability description is exact for both the near-field and far-field, in the limiting case of a lossless ENZ host.

Deploying nonlinear dielectrics as the dopants, the effective permeability description remains valid. In this case, as the intensity of the incident field increases, the stronger electric fields inside the nonlinear dopants lead to a modification of the permittivity of dopants with perturbative Kerr nonlinearity. In turn, the magnetic field distribution inside the nonlinear dopants is modified, leading to a variation in the effective permeability of the doped ENZ in response to the increased incident intensity. By judiciously selecting the dielectric dopants’ size, geometry, or permittivity, it is possible to engineer the structure such that the effective permeability changes considerably with a moderate incident intensity; hence, leading to a non-perturbative magnetic nonlinearity by merely introducing non-magnetic Kerr dielectric inclusions into a non-magnetic linear ENZ host.

2. Concept

Among the peculiar properties of ENZ media, it has been shown that the magnetic field inside a 2D ENZ (i.e. infinitely extended in the out-of-plane direction) is spatially invariant for the TM polarization[4]. Inserting dielectric inclusions inside the ENZ host does not disturb the spatial uniformity of the magnetic field inside the ENZ; however, the dopants affect the total flux through the ENZ. As a result, it has been theoretically and experimentally verified that such a doped ENZ medium maintains its near-zero effective permittivity, \( \varepsilon_{\text{eff}} \approx 0 \), while exhibiting a modified effective permeability \( \mu_{\text{eff}} \neq 1 \) where \( \mu_{\text{eff}} \) is found by finding the magnetic flux through the doped ENZ by integrating the magnetic field distributions over each dopant[5].

Figure 1: (a) An ENZ host doped with dielectric dopants. (b) The corresponding effective medium description.

3. Applications

Numerous designs for electromagnetic absorbers have been proposed in the recent decades for a wide range of applications[6]. Despite the vast literature on linear absorbers, only a handful of studies have been focused on
nonlinear absorbers which may be useful for applications such as optical limiters. Therefore, we illustrate the utility of the enhanced nonlinearity obtained from doping ENZ media in the context of designing nonlinear absorbers.

Consider an ENZ slab periodically doped with a Kerr dielectric rod backed by a PEC ground plane. Placing a sheet with resistivity \( \rho_0 (\Omega/\text{cm}) \), with \( \rho_0 \) denoting the free-space intrinsic impedance, on top of the grounded ENZ slab leads to a design for a nonlinear absorber. The operation mechanism of such an absorber is readily understood by noting that a doped ENZ slab, with thickness \( d \), may be modeled by a lumped series reactance given by [7]:

\[
X(\omega) = \omega \mu_0 \mu_{\text{eff}} d,
\]

Assuming the size of the dielectric inclusion is chosen such that \( \mu_{\text{eff}} \approx 0 \) for a low-intensity incident wave, the input impedance seen behind the resistive sheet is negligible, leading to effectively short-circuiting the resistive sheet. As a result, for low-intensity illumination, the absorption is negligible. On the other hand, an increasing incident intensity translates to an increase in the effective permeability of the doped ENZ slab, leading to increased sheet absorption as a result of the higher input impedance behind the sheet. In this manner, a reverse saturable absorption characteristic is obtained where the absorption increases with incident intensity.

4. Conclusions

In summary, we have theoretically demonstrated a novel approach for designing ENZ metamaterials with enhanced nonlinearity. Our technique, which can be applied to any frequency regime where a sufficiently low-loss ENZ and a nonlinear material exists, allows one to obtain a strong magnetic nonlinearity using a single inclusion with a relatively weak electric nonlinearity. We illustrated this concept by incorporating such nonlinear metamaterials for designing nonlinear absorbers, as an example for the various potential applications.

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References


Plasmon-assisted multipolar terahertz absorption spectroscopy in graphene

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Abstract

We explore plasmon-enhanced absorption spectroscopy showing that multipolar rotational transitions of molecules in proximity of localized graphene structures can be accessed thanks to terahertz plasmons. In particular we consider H₂⁺, demonstrating that graphene micro-rings provide a giant field localization enabling the enhancement of the absorption cross-section by 8 orders of magnitude.

1. Introduction

Light-matter interactions play a major role in the development of several spectroscopic techniques enabling molecule identification by their spectral fingerprints. Nanophotonics further provides a rather unique platform to increase radiation-molecule interaction through the tight confinement and large field enhancement produced by plasmons, i.e., the collective excitations of conduction electrons in metals, thus enabling surface-enhanced infrared absorption (SEIRA) and surface-enhanced Raman scattering (SERS). Doped graphene offers an appealing alternative to noble metals because it sustains electrically tunable surface plasmons at infrared and THz frequencies, thus enabling label-free SERS and SEIRA [1]. Here, we explore the potential of localized graphene plasmons for multipolar surface-enhanced terahertz absorption spectroscopy (SETAS) of dipole-inactive molecules. In particular, we demonstrate that the strong-field enhancement and the deep subwavelength features of THz plasmons in a graphene microring with a nano-hole at the core generate sharp peaks at the inner and outer edges such that the multipolar absorption cross section of nearby molecules increases enormously. Specializing our calculations to H₂⁺ we observe that its plasmon-enhanced average quadrupolar absorption cross-section increases up to eight orders of magnitude with respect to homogeneous plane-wave excitation. Our calculations further illustrate the detailed angular momentum exchange between the molecule and the impinging radiation, indicating that plasmon-enhanced radiation spin–orbit interaction [2,3] opens transition channels for all molecular orientations. Our results constitute a solid theoretical basis to support graphene as an ideal platform for electrically tunable multipolar SETAS at the nanoscale [4].

2. Discussion

Multipolar absorption is an inherently weak process as it ensues from the electromagnetic field spatial variation within the molecule. In the far-infrared and terahertz regions of the electromagnetic spectrum molecules typically possess purely-rotational transitions, while purely vibrational or mixed roto-vibrational transitions typically happen in the mid-infrared. We consider the H₂⁺, which possesses rotational energy levels E_J = B(J + 1), where B = 29.8 cm⁻¹.

We investigate the molecule–radiation interaction by the Power–Zienau–Woolley scheme and by solving perturbatively the density matrix equations of the molecule, calculating the molecular absorption cross-section σ_mol accounting for quadrupolar transitions. Averaging over all possible molecular orientations, we obtain the results depicted in Fig. 1, where in (a) we show the dependence of the plasmon-enhanced molecule absorption cross-section σ_mol over the in-plane radius and altitude, while in (b) we illustrate the altitude dependence of σ_mol averaged over the disk. absorption cross-section of molecules in vacuum σ_vac.

Figure 1: (a) Contour plot of σ_mol rescaled to σ_vac averaged over all molecular orientations as a function of r⊥,z. (b) Averaged absorption cross-section as a function of z.
Note that graphene enables the enhancement of the quadrupolar transition cross-section by 16 orders of magnitude locally for molecules nearby the inner graphene edge. The averaged enhancement factor $\sigma_{mol}/\sigma_{vac}$ ranges from $10^6$ to $10^9$ for molecules at altitudes between 1 nm and 50 nm.

3. Conclusions

Our calculations indicate that enhanced multipolar THz absorption spectroscopy can be attained through graphene plasmons, thus enabling the identification of dipole-inactive chemical species. The enhancement factor of the molecular absorption cross-section locally reaches values as high as $10^{16}$, while in average lies between $10^7$ and $10^9$, depending on the altitude of the molecule over the graphene ring.

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References


Materials for nonlinear optical metasurfaces

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Key-words: plasmonics, metasurfaces, multipolar interference, nonlinear generation, plasmonic materials, hyperbolic materials

Plasmonic and metasurface systems have allowed for the exploration of unprecedented optical properties and phenomena using widely available materials such as noble metals[1]. As the field advances, researchers have begun to explore dynamic, tunable, and nonlinear phenomena in metamaterials and plasmonics with the aim of developing technologically relevant responses[2]. Plasmonic and metamaterial systems are potentially enabling to many relevant technologies, and we are investigating applications in detecting optical signals in the mid and long wave infrared, and the generation, detection and conversion of single photons for quantum information applications that are significant to a range of Air Force technologies. These studies drive research to increase performance and functionality within the metasurface system based on optimized design and better material performance.

In this presentation we will explore efforts to create nonlinear metasurfaces with engineered properties and ongoing efforts to develop materials capabilities that will support their further development. Nonlinear metasurfaces have a broad range of application and we explore how nonlinear properties of metasurfaces can be engineered for quantum information applications as a specific avenue. We show that nonlinear multipole interference allows both non-reciprocal and unidirectional nonlinear generation from nanoelements or their periodic arrangement in a metasurface, with the direction of nonlinear generation preserved with respect to a fixed laboratory coordinate system when reversing the direction of the fundamental field. Alternatively, balanced multipolar generation can ensure a directionally selective inhibition of the nonlinear response for certain respective directions of the fundamental beams[2]. We attribute the presented phenomena to the existence of the common (electric or magnetic) pathways inducing the electric and magnetic Mie resonances via a nonlinear interaction as shown in figure 1, such that switching the phase of one (electric or magnetic) of the vectors of the fundamental field can change simultaneously the phase of all (electric and magnetic) nonlinearly generated multipoles[3]. Furthermore, the interference can occur between various effective hyperpolarizability terms within the electric and magnetic (nonlinearly produced) dipolar modes themselves. Both cases are example where the engineering of materials response through structure to achieve desired optical properties can enable new potential technologies.

Figure 1 Nonlinear generation from dimer structures with controlled multipolar response allows for the selective enhancement and suppression of various nonlinear generation "pathways"
To support the development and demonstration of nonlinear metasurfaces, we are exploring novel materials systems that can achieve the dimensions and properties required to control nonlinear response. In general, the thicknesses and uniformity required from nonlinear metasurfaces, specifically of the type we propose which have complex dimer or cut wire pair type substructure, are challenging to achieve. Dimensions of a few 10s of nm thickness are required and spacer thicknesses, interfacial quality, and material orientation become critical for uniform metasurface response as shown in figure 2. Many conventional materials systems such as noble metals and conventionally deposited thin films are not suitable or do not support the optimum structures. Moreover, for nonlinear effects in metasurfaces, high optical excitation intensities are often required and can be enabling for a broader range of applications. As such more resilient materials are needed[5]. To advance the palette of materials available and thereby advance the functionality of metasurfaces, we are exploring systems that support epitaxial growth of high precision layered structured. Investigation of both transition metal nitride and arsenide based systems is ongoing. In each case, the control of linear and nonlinear properties, deposition of ordered hetero-structures, and the structural control of these materials provides novel engineering control for metasurface applications. We will review current progress in these efforts and discuss future device capabilities that are enabled by the work.

References.

Transdimensional photonic lattices with van der Waals metasurfaces and strong coupling to high-index thin layers

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Abstract

Recently, transition metal dichalcogenides (TMDCs) from the family of van der Waals layered materials have been shown to exhibit tailorable optical properties along with strong nonlinearity, high refractive index, and anisotropy. We envision that TMDCs is a promising material platform for designing ultra-thin optical elements. Here, we investigate a van der Waals metasurface that consist of disk-shaped nanoantennas made of a TMDC material, tungsten disulfide, placed on top of a thin intermediate layer of high-index material such as silicon and low-index oxide substrate.

1. Introduction

Nanoparticles of high-refractive-index materials like semiconductors enable strong confinement of light at the subwavelength scale because of the strong reflection from material boundaries and excitation of Mie resonances within the nanoscale-size particle. We show that TMDCs can be used as a material platform for designing metasurfaces and ultra-thin optical elements: these van der Waals materials show a strong spectral response on light excitations in visible and near-infrared ranges, and nanostructure characteristics can be controlled by nanoantenna dimensions and their arrangement [1].

2. Model

Here, we investigate a periodic array of disk-shaped nanoantennas made of a TMDC material, tungsten disulfide, placed on top of a thin intermediate layer of high-index material such as silicon and low-index oxide substrate. Planar photonics with efficient subwavelength light control can be designed based on transdimensional lattices that operate in the translational regime between 2D and 3D [2]. Such transdimensional lattices include 3D-engineered nanoantennas supporting multipole Mie resonances and arranged in the 2D arrays with collective effects. The periodic arrangement of the nanoantenna array facilitates the strong coupling of light into the thin high-index layer. We show that the nanostructure resonances and coupling between nanoantennas and substrate in TMDC disk-shaped nanoantenna array can be controlled by the variation in silicon layer thickness and have a dependence on the presence of index-match superstrate cover.

3. Discussion

In our research, we show that nanoantennas made of TMDC materials can achieve spectrally tunable resonances with a...
possibility of their efficient control both in single and collective forms. In particular, in this work, we investigate scattering properties of van der Waals nanoantennas, made of tungsten disulfide WS$_2$, and the possibility of using these TMDC nanoantennas in ultra-thin optical components and metasurfaces. We theoretically demonstrate the excitation of optical resonances in the visible and near-infrared spectral ranges in the nanodisks with the dimensions of hundreds of nanometres on a silicon oxide substrate with an intermediate silicon layer. We show that resonances in the nanoantenna array can be controlled by the thickness of the silicon layer, and the variation in the superstrate layer can affect spectral features in the absorption and reflection profiles.

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**References**


Metasurface design and application for compact AR device

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Abstract

The principles and applications of metasurface will be given with detailed examples. Three metasurface designs that can exceed the conventional optical modulation will be given, which are complex-amplitude modulation, full-space visible light modulation, and phase-change material-based metasurface. Then, metalens eyepiece for augmented reality will be discussed.

1. Introduction

Metasurfaces, considered as the future optic components thanks to their planar and lightweight characteristic, have been explored by various research groups for novel-type modulation of light [1-3]. They have been employed to many optic devices that desire compactness and novel optic components, such as augmented reality [4], microscopy [5], and other devices requiring lenses [6]. In this context, unprecedented light control through metasurfaces has also been studied a lot by the expectation in that they can pave the way to design completely new optical setups.

In this invited talk, several optical metasurface mechanisms or applications are proposed for next generation optical systems. The first topic is about metasurface holography, an optical technology which reproduces wavefront of light as desired manner. Conventional dynamic holographic display has way to go with light modulators due to their large pixels which are larger than operational wavelength and lacking modulation performance to be used in real optical devices. On the other hand, metasurfaces have been presented to have subwavelength pixel pitch and relatively high modulation performance. Here we discuss the holography generated by three metasurfaces: One enables full complex-amplitude control, and another has ability to impart unrelated hologram to transmission and reflection space, respectively. Finally, the other one utilizes phase-change material to realize active phase-profile change through heat bias. As an application example, augmented reality (AR) imaging is studied. AR is a technology that combines real and virtual images together. One can see both the virtual image and the real scene at the same time thanks to AR device that creates virtual information in the real world. AR is a promising technology, proven by a lot of products by various companies. However, conventional optical components suffering limited performance and functionality make it impossible to realize compact and lightweight AR display system with high performance. In this context, we propose a novel scheme of combining the metasurface into AR system, which in turn shows improved high performance, dubbed as a see-through metalens. This presentation will discuss current issues of the conventional AR device and we show potentials and challenges in metasurfaces applications further.

2. Results and Discussion

2.1. Metasurface designs for unprecedented light control

Figure 1: Our proposed metasurface designs (a) X-shaped meta-atom for complex-amplitude modulation [7]. (b) Operational mechanism of the bifacial metasurface [8]. (c) Schematic diagram of phase-change material-based metasurface tuned by heat bias [9].

Our recent research aims to pave the way to exceed the conventional modulating ability of spatial light modulators. Firstly, we used X-shaped meta-atoms which provide broadband and independent control of amplitude and phase in subwavelength pixel, which is tricky to be realized simply by traditional holographic method and most of conventional metasurface holography [7]. This X-shaped structure employs Pancharatnam-Berry phase for broadband operation in visible region and is theoretically proved to modulate the amplitude and phase according to the relation of geometric angles of X-shape. It was possible to implement full complex-amplitude hologram with 350 nm pixel pitch, as shown in Figure 1a, reporting to have saturated noise compared to conventional metasurface holograms.

Our research on metasurface expanded the modulation performance, which leads to the increase of information that one metasurface can carry by utilizing full-space control [8]. By utilizing the spatially varying meta-atoms, the multipole
coefficients that contribute to the phase difference between transmission and reflection space are altered. As a result, we designed a novel metasurface which enables the independent phase control of reflection and transmission space, called bifacial metasurface. As shown in Fig. 1b, generated hologram images are altered depending on the viewing direction.

Fig. 1c shows our active metasurface platform, which is composed of phase change material, Ge_{2}Se_{5}Te_{3} (GST) [9]. The unit cell consists of two C-shaped meta-atoms, and each of them operates at specific material phases, amorphous or crystalline phase. Since the phase of GST can be tuned by heat bias or pulsed laser intensity, the imparted phase profile can be tuned by the external bias, and this property is employed here to change the generated holographic images.

2.2. Metasurface lens eyepiece for AR device

Figure 2. (a) Schematic diagram of proposed AR device integrated with metasurface lens [4]. (b) Captured images of fabricated sample. Left image is captured by camera, and right image is captured by scanning electron microscope. (c) Experimental results of AR by three colors, showing virtual image of letters (RED, GREEN and BLUE) and real image of toy car.

Metasurface lens, called metalens, has been used in various researches thanks to its ultracompact and lightweight nature compared to refractive lens [5]. We applied metalens into eyepiece at AR system. As a solution of the chronic field-of-view (FOV) problems of conventional AR displays, metalens can pave the way to provide improvement of this problem. In commercial AR display, large lenses with low numerical apertures (NAs) offer a FOV of only 30° with realistic compromise. Here, we present a see-through metalens with a high NA and a dual functionality which allows metalens to be located right in front of the human eye, as shown in Fig. 2a. See-through metalens is designed to be a lens with high NA for the virtual information, and a transparent glass for the real information. As shown in Fig. 2b, the proposed metalens is fabricated through nanoimprint and electron beam lithography to have lens diameter of 2 cm and NA of 0.6, which leads to very wide FOV of 100°.

Measured AR images are shown in Fig. 2c, and this shows the virtual and real images are successfully generated as desired. This AR application via metasurfaces will lead the steps in relating the AR displays to nanophotonics, and it is expected to be a promising solution for the future optic display.

3. Conclusions

In this invited talk, several metasurfaces which show hologram and unprecedented manipulation of light properties are discussed. We present physical mechanism and conceptual illustration of the recent metasurfaces as well. Then we introduced three metasurfaces, which can be applicable in future optic devices. As an application example of metasurface device, we present and discussed the AR device integrated with metasurface lens as an eyepiece. Finally, we will discuss our perspective on this area with application to real optic devices.

Acknowledgments

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References

Enhanced Hot Carrier Effects Using Ultra-Thin Metal Films, Alloys, And Index Near-Zero Substrates

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Abstract

Bulk metals are good reflectors of light; however, ultra-thin films and nanostructures composed of these same materials can create highly absorptive systems. One recent approach has been to use subwavelength resonances in ultra-thin films, which can achieve absorption above 70%, approaching the theoretical limit using traditional substrates. Here we show that ~100% absorption is achievable provided that the ultra-thin metals are deposited on an index near zero (INZ) substrate. We further demonstrate that this absorption can be used to generate photocurrent through the transfer of energy from the photons to the free electrons in the metal. Using different ultra-thin metals and alloys, we are able to tune the mean-free-path of the carriers to enable new designs for efficiency hot carrier optoelectronic devices.

1. Introduction

When light is incident on a thick metal film, it is predominately reflected, giving rise to a simple mirror. However, if the film is very thin, non-trivial phase shifts occur both within the material and upon reflection at the interfaces, giving rise to strong interference effects and the possibility of high absorption in films that would otherwise reflect the incident light. As an example, when near-IR light is incident on a thin metal film from a high index substrate (e.g. Si), nearly 80% of the light can be absorbed over a broad frequency range [1]. Similarly, ultrathin metal-insulator-metal stacks can give rise to photocurrent generation without the need for a semiconductor [2-4].

The basic principles behind hot carrier generation and collection are shown in Fig. 1. For this configuration, near-IR light (1100-1800 nm) is incident on a Si wafer through a SiN_x antireflection coating. Because Si is non-absorbing over this wavelength range, the light passes through the wafer and is incident on the thin metal film on the back. For thick films, the light is mostly reflected; however, for film thicknesses ~20 nm, between 70-80% of the light can be absorbed in films of Pt, Fe, Cr, and Ti. Depending on the electron density of states (EDOS) of the material, hot carriers will be generated upon photon absorption. Electron-electron interactions will cause a redistribution of the energy and eventually electron-phonon interactions will cause a cooling of the electron temperature as energy is dissipated in the lattice. However, many of the excited charge carriers are able to travel to the metal-semiconductor interface before losing too much energy and can be injected across the Schottky barrier (Fig. 1b).

Figure 1: Hot carrier excitation and collection. (a) Schematic of a metal-semiconductor hot carrier device. (b) Energy band diagram. An incident near-IR photon travels through the Si and is absorbed in a thin metal layer at the back of the device. The absorption leads to hot electrons, some of which will have enough energy to be injected across the Schottky barrier into the Si, where it is collected as current.

2. Discussion

We have recently explored the use of traditional metals such as gold [2] and aluminum [3], as well as platinum, iron, chromium, and titanium [1] for hot carrier devices. These
materials have tradeoffs in terms of absorption and carrier mean-free-paths that must be considered for device applications. Further, alloys and nanostructures are also promising candidates [5].

To increase the absorption within a metal film, we also utilize a subwavelength Fabry-Perot-like resonance in conjunction with an index-near-zero (INZ) substrate to achieve near-unity absorption and hot carrier photocurrent in nanoscale metal films [6,7]. By employing aluminum-doped zinc oxide (AZO) as the INZ medium in the near-infrared range, we enhance the metal film absorption by nearly a factor of 2. To exploit this absorption enhancement in an optoelectronic device, we fabricate a Schottky photodiode and find that the photocurrent generated in Pt on Si is enhanced by >80% with the INZ substrate. The enhancement arises from a combination of improved carrier generation and carrier transport resulting from the addition of the AZO film.

Figure 2: Near-perfect absorption in real metals on nearly ideal INZ substrates [6]. The calculated absorption in thin film Cr, Ti, Fe and Pt illuminated from air is near unity with an INZ substrate \(n = 0.01\). Solid and dashed lines are the absorption with and without the INZ substrate, respectively. The gradient in color depicts the different metals. The red arrows in the diagrams show illumination direction.

This presentation will describe the various aspects and design considerations necessary for developing future hot carrier devices, including near-IR photodetectors based on these concepts.

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References


Metaphotonics meet fibers: a novel pathway towards boosting in-coupling efficiencies and single-fiber optical trapping

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Abstract

Here we present that interfacing optical fiber with nanostructures defines a novel class of fiber-integrated devices – nanostructure-interfaced fiber – allowing to reach new domains of applications for Fiber Optics research. Through 3D nanoprinting and modified electron-beam lithography, we integrate high NA-meta-lenses and dielectric ring gratings onto the end faces of single mode fibers. These devices allows for efficient light in-coupling at angles as large as 80° and for trapping polymer microbeads with one single-mode fiber device.

1. Introduction

The interfacing of nanostructures with the end faces of commercially available optical fibers represents a promising approach to unlock novel types of functionalities within a multitude of fields including biophotonics, quantum technologies or optical sensing. Commonly used top-down fabrication strategies are hard to employed in case fibers are considered due to the intrinsic dimension mismatch of the fiber geometry with wafers.

Within this presentation, we report on our recent results that consider two fabrication methods to circumvent the mentioned bottleneck, namely (i) modified electron-beam lithography [1] and (ii) 3D nano-printing [2]. Both approaches allow for the implementation of nano-structures on the end-face of optical fibers leading to significant performance improvements compared to fibers with blank end faces. These improvements are shown here on the examples of (i) boosting in-coupling efficiencies into fibers at almost grazing incidence via dielectric nano-structures [3] and (ii) optical trapping of micro-beads using only one single-mode fiber via the integration of dielectric meta-lenses [2].

2. Boosting in-coupling efficiencies

Optical fiber are particular difficult to use within the context of wafer-based technologies due to the large aspect ratios of fibers, being complementary to wafers. Using an additional planarization step prior to nano-fabrication we open up a pathway to integrate dielectric nano-structures onto the end-face of optical fibers via electron-beam based technology.
1, 4]. Specifically, we show that by integrating dielectric gratings consisting of concentric rings located on the core of single-mode fibers (Fig. 3 top), in-coupling efficiencies can be increased by more than four orders of magnitude at almost grazing incidence compared to fibers with unstructured end faces (Fig. 2 bottom) [3]. Application relevant in-coupling efficiencies of several percent at angles of more than 80° have been reached, suggesting a clear pathway to solve one serious bottleneck of optical fibers which has imposed limitations on applications of optical fibers.

Figure 2: (top): High refractive index ring gratings (made from SiN) located on a bundle of seven single-mode fibers. (bottom) Measured coupling efficiency vs. angle of incidence for the bare fiber (dashed gray) and the nanostructured-interfaced fiber (wavelength: 1.55µm). The colors refer to different number of rings [3].

3. Optical trapping with single fiber

A tight focus of light plays an essential role in a vast number of applications including optical imaging, optical manipulation, material processing, biophotonics, microscopy and quantum technology. Here optical fibers show fundamental limitations due to the divergence of light emerging from the fiber facet which for instance has limited the use of single fibers within optical trapping, demanding numerical apertures >0.8. In this presentation we show that 3D nano-printing via direct laser writing allows for the integration of ultra-high numerical aperture meta-lenses on the facet of functionalized single-mode fibers (Fig. 3 top) [2]. Via taking into account the peculiarities of the fiber environment record-high numerical apertures of up to 0.9 and diffraction-limited spots have been reached. The capabilities of this device have been demonstrated by optically trapping microbeads and biologically relevant bacteria (E. coli) for the first time with a single single-mode fiber (Fig. 3 bottom), again solving a serious limiting factor within fiber optics research.

Figure 3: (top): Nanoprinted metalens on modified single-mode fiber [2], (bottom): trapped E.coli. bacteria in front of the meta-lens interfaced modified single-mode fiber.

4. Conclusions

We have demonstrated that the interfacing of optical fibers with nanostructures yields a novel class of fiber-integrated devices with application beyond what is state-of-the-art within fiber optics. Due to the flexibility of the application strategies used, we expected further application of nanostructure-interfaced fibers in a multitude of fields such as quantum technology, bioanalytics and nano-photonics

References

Single-Emitter Near-Field Excited Quantum Dynamics in Near-Zero-Index Materials

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Abstract

We investigate the quantum dynamics from single quantum emitters (QE) excited using near-field light from a plasmonic transducer. Results show the ability to strongly drive a QE using a plasmonic near field with an ultrafast single-photon emission rate of $10^{15}$–$10^{14}$ fs$^{-1}$ for emitters embedded in near-zero index (NZI) media. QEs embedded in NZI media also demonstrate excellent enhancement of spontaneous emission compared to those in free space ($\approx 10^7$). Comparisons are made using QEs embedded in other common materials such as Silicon.

1. Introduction

Since early reports on sub-diffracted light produced from a plasmonic near-field transducer (NFT) in 2009 [1], efforts have dramatically increased to utilize this nanoscale source of channeled light within a number of quantum and classical devices. NFTs are not only able to replace the use of an integrated, and often stationary, cavity structure but they can be moved, i.e. rastered, across media surfaces [2]. This makes NFTs highly suitable for applications such as optical communications, phononic lasers, medical devices, and information processing [2, 3]. Notably, it has the desired characteristic to be physically separated from the surface morphology that the light is incident upon such as recording media, biological tissue, or quantum circuitry. Recent advances in the fabrication of NFTs and similar-sized plasmonic nanostructures has been realized experimentally [4], thus proving their use to be more accessible, in particular for producing single-photon emission, i.e. photon antibunching, which is envisioned as a source for entangled qubits in quantum technologies. Herein, we describe our system (NFT + media) and demonstrate efficient, near-field excited ultrafast (femtosecond) emission of single photons without an integrated cavity structure, with a particular focus on NZI materials [5]. Comparisons are made using QEs embedded in NZI media, particularly known for improved absorption at the NZI wavelength, along with other materials such as Si-based QEs or QEs in free space. Dynamic manipulation of the single-photon emission rate as well as the enhancement of the spontaneous emission is shown to not only be possible but controllable as a function of input power and materials used.

2. Methods

We use the NFT shown in Fig. 1a to couple a photonic mode of 820 nm with an antisymmetric surface plasmon mode of the NFT. All material parameters used and their physical dimensions are identical to those outlined in [2]. A solitary quantum dot embedded in a thin film is placed roughly 10 nm in front the NFT. Its dipole moment is considered aligned with the corresponding optical field profile produced by the NFT shown in Fig. 1b. Remarkably, this nanoscale profile has enough power to strongly drive the QE, i.e. the mode splitting, defined by $g = \mu \cdot E(r)$ where $\mu$ is the dipole moment of the QE, is greater than the modal decay rate in this case by an order of magnitude. Therefore, numerous controlled processes can occur before full dephasing has occurred. The time-dependent density matrix of a 2-level QE [2] and Maxwell’s equations are solved simultaneously, where the Hamiltonian of the QE is given by

$$H = \omega \sigma^+ \sigma^- + \mu E^z (\sigma^+ + \sigma^-),$$

(1)

with $\omega$ being the resonant frequency of the emitter and $\sigma^\pm$ the raising or lowering energy level operators. $E^z$ is the total
scattered field at the position of the QE. The multiscale physics simulation is coupled together when calculating the ensemble average of the QE’s polarization and including its effect on the nearby scattered field.

The autocorrelation function which quantifies antibunching by comparing measurements or calculations taken at two different times is defined as \( g^{(2)}(\tau) = \langle I(t) \cdot I(t + \tau) \rangle / \langle I(t) \rangle^2 \), where \( I \) is the intensity. The function is normalized such that for single photons to dominate the emission process one needs values below 0.5. This function is neatly reduced using density matrix formalism since \( \langle I(t) \rangle = \eta \gamma_r \rho_{zz}(\infty) \), where \( \eta \) is the collection efficiency of the detection system and \( \gamma_r \rho_{zz} \) is the rate at which photons are emitted. \( \gamma_r \) is the radiative decay \( (8 \times 10^{11} \text{s}) \) and \( \rho_{zz}(\infty) \) is the steady state probability of occupying the emitter’s excited state, which therefore yields \( g^{(2)}(\tau) = \frac{\rho_{zz}(\tau)}{\rho_{zz}(\infty)} \). The calculation of the autocorrelation function is analogous to performing the Hanbury Brown-Twiss experiment [6].

3. Results and Discussion

We focus primarily on the behavior of QEs embedded in near-zero index films where for light at the NZI frequency we see an increase in absorption of the electric field which in turn is able to more strongly drive the transition between the ground and excited states. Fig. 2 shows the ultrafast oscillation rate of the autocorrelation which is related to the Rabi oscillation rate of the emitter. The Rabi oscillation rate, being proportional to the mode splitting, dictates transition times between the excited and ground state of the QE. Single photons are emitted faster if the QE is embedded in NZI material due to the increased electric field intensity. That is compared to Si-based emitters (yellow curve) and emitters in Vacuum while on the surface of Si (blue curve), though efficient photon antibunching also occurs using these materials.

In order to calculate the enhanced spontaneous decay rate \( (\gamma_{sp}) \) and compare it to the free space decay rate \( (\gamma_0) \) we must solve for the following [2],

\[
\gamma_{sp} = \frac{\pi \alpha |p|^2}{3 \hbar} \delta(r - r_1) \eta(r_1, \omega_1),
\]

\[
\gamma_0 = \frac{\omega_1 |p|^2}{3 \pi \hbar^2 \epsilon_0}
\]

where \( \mathbf{p} \) is the ensemble averaged polarization of the QE. This requires us to first calculate the dyadic Green’s function in order to retrieve the partial local density of states,

\[
\eta(r_1, \omega_1) = \frac{6 \omega_1}{\pi \epsilon_0^2} [\mathbf{n}_p \cdot \mathbf{G}(r_1, r_2; \omega_1) \cdot \mathbf{n}_p],
\]

with \( \mathbf{n}_p \) the unit vector of the dipole moment. The dyadic Green’s function is derived from the time-varying electric field and polarization at the position of the \( \mathbf{QDE}(r) = \omega_1^2 \mu \rho_0 \mathbf{G}(r, r_1) \mathbf{p} \). Calculations reveal the excellent enhancement of the spontaneous emission rate \( (10^7) \) for QEs embedded in NZI material while rates are enhanced an order of \( 10^8 \) for Si-based QEs and QEs in Vacuum, respectively. This compares well to nanoantenna and gap plasmon designs with typical enhancements on the order of \( 10^7-10^8 \). Altogether results are deemed promising as a single-photon source, where we have demonstrated dynamic control of the emission rate suitable for ultrafast quantum information using emitters embedded in highly absorbent NZI films.

Acknowledgements

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References


Near-infrared Active Metasurfaces for Tunable Beam Diffraction and Dynamic Polarization Conversion

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Abstract
In this talk, I will firstly discuss an all-dielectric active metasurface platform based on electro-optically tunable III-V multiple-quantum-well (MQW) resonators. By selectively applying an electrical bias to metasurface elements, we experimentally realize a dynamically switchable diffraction grating and beam steering. Subsequently, I will report a scheme of active polarization modulation by using indium tin oxide (ITO)-based tunable metasurfaces. By suitably biasing the metasurface structure, the polarization of reflected light can be converted to versatile states.

1. Introduction
Tunable metasurfaces enable active control of key constitutive properties of light at a sub-wavelength scale [1,2]. Dynamic metasurfaces are typically achieved by either incorporating active materials, such as tunable plasmonic structures or thermo-optically responsive media, into otherwise passive metasurface structures or directly utilizing tunable media as the resonant elements [3,4]. In this talk, I will discuss two difference scenarios of dynamically modulating the light properties with active metasurfaces at near-infrared (NIR) wavelengths. Firstly, I will report an all-dielectric active metasurface platform based on electro-optically tunable III-V multiple-quantum-well (MQW) resonators [5]. By applying a DC electric field across the MQW resonators, we dynamically modulate modes supported by the hybrid Mie-guided mode (Mie-GM) resonant metasurface elements. We experimentally observe a relative reflectance modulation of 270% accompanied with a continuous phase shift from 0° to 70°. In addition, we use our all-dielectric tunable metasurface to demonstrate a dynamically switchable diffraction grating and beam steering. Subsequently, I will discuss a scheme of active polarization modulation by using indium tin oxide (ITO)-based tunable metasurfaces [6]. By suitably biasing the metasurface, the carrier concentration at the gate-dielectric/ITO interface is modulated, resulting in a change of the effective index of the ITO layer [7]. The epsilon-near-zero (ENZ) mode, which is accessed under applied external DC bias, alters the interaction between the induced plasmonic modes, leading to modulation of the polarization state of the reflected light.

2. Results and discussions
2.1. All-dielectric active metasurface
We report an all-dielectric active metasurface platform based on electro-optically tunable III-V multiple-quantum-well (MQW) resonators to realize active metasurfaces. In this work, we design an epitaxial III-V compound heterostructure, comprising a distributed Bragg reflector (DBR) and a 1.23 μm-thick MQW layer grown on GaAs substrates, as shown in Fig. 1(a). The DBR, which is used as a dielectric mirror, is comprised of 20 pairs of alternating layers of n-Al0.9Ga0.1As (76.5 nm) and n-GaAs (65 nm) with the n-Al0.9Ga0.1As as the topmost layer. We exploit the quantum-confined Stark effect in GaAs-based MQW hybrid Mie-guided mode (Mie-GM) resonators to actively control the optical response of the metasurface phase and amplitude at near-infrared wavelengths.

Figure 1: (a) Schematic of the all-dielectric active metasurface. (b) Measured reflectance modulation of the MQW resonators for different applied electrical bias [5].

By applying a DC electric field across the hybrid Mie-GM resonators, we dynamically modulate modes supported by the Mie-GM-resonant metasurface elements. We experimentally observe a relative reflectance modulation of 270% (see Fig. 1b) accompanied with a continuous phase shift from 0° to 70°. In addition, we use our all-dielectric
tunable metasurface to demonstrate a dynamically switchable diffraction grating and beam steering. By selectively applying an electrical bias to metasurface elements, we can electronically modulate the metasurface period, enabling on-off switching and steering of the first-order diffracted beam.

2.2. Tunable polarization meta-converter

Aside from abovementioned all-dielectric metasurfaces, we also report a hybrid ITO-metal metasurface for active control of light polarization. Optical polarization is an important characteristic of electromagnetic waves that has a significant impact on a number of applications, including communications, 3D imaging, and quantum computation. In this work, we demonstrate that the polarization state of reflected light can be dynamically controlled by an indium tin oxide (ITO)-based tunable metasurface [6]. Figure 2 illustrates the proposed metasurface which consists of an Al back reflector, a 20 nm thick dielectric layer and a 5 nm-thick ITO layer on which we fabricate an Al nan-antenna array. The period of the metasurface structure is 400 nm while the operating wavelength is 1580 nm. When applying an electrical bias between the ITO layer and back reflector, the carrier concentration at the gate-dielectric/ITO interface is modulated, resulting in a change of the effective index of the ITO layer.

Figure 1: Schematic for the tunable polarization using hybrid ITO-metal metasurface.

The epsilon-near-zero (ENZ) mode, which is accessed under applied external DC bias, alters the interaction between the induced plasmonic modes (which correspond to the orthogonal polarization components), leading to modulation of the polarization state of the reflected light. By suitably biasing the metasurface structure, the linearly-polarized incident light can be converted to cross-polarized, circularly-polarized or elliptically-polarized light.

3. Conclusions

In summary, we have demonstrated active optical modulation through two different approaches: all-dielectric tunable metasurface and hybrid ITO-metal metasurface. All-dielectric active metasurface platform is realized based on an electro-optic effect in III-V compound semiconducting MQWs. By tuning the coupling between electron transitions in quantum confined Stark effect in MQW and hybrid Mie-GM resonant mode via electrical bias, we further experimentally demonstrate tunable beam diffraction at NIR region. For the hybrid metasurface, design concept exploits the strong permittivity modulation of conducting oxides near the ENZ condition, enabling tunable polarization conversion in the NIR. Such dynamic controls of the amplitude, phase as well as the polarization state of the scattered beam provides prospects for various applications, such as dynamic wave plates, low-profile spatial light modulators, adaptive wavefront control, signal monitoring and detection.

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References

Generating High Resolution Accelerating Optical Beams and Beam Array Based on All-dielectric Metasurfaces

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Abstract

We experimentally realize high-resolution Airy optical beams and beam array with long working and non-diffraction propagation distances based on our proposed highly compact all-dielectric synthetic metasurfaces, that integrate a cubic phase and the phase of a Fresnel holographic lens. In addition, we demonstrate that imposing the phase of a Dammann grating to the above synthetic metasurface produces an array of Airy optical beams.

1. Introduction

Airy optical beams exhibit fascinating characteristic properties of diffraction-free, self-accelerating and self-healing, enabling a wide range of exciting applications in pleninous fields of photonics. The experimental realization of Airy optical beams are typically generated by commercial spatial light modulators (SLMs) made of liquid crystal, in combination with purposely designed bulky optical elements[1]. Large pixel and pitch sizes of the SLMs, on the order of tens of the incident light wavelength, lead to the limited resolution of the phase discretization.

To date, several pioneering works have demonstrated the use of ultrathin plasmonic or dielectric metasurfaces to generate high-resolution, high-efficiency, multi-wavelength, even broadband, and spin-controlled Airy beams by either simultaneous amplitude and phase manipulation or phase-only manipulation[2,3]. However, little attention has been paid to the relationship between working distances of the devices, non-diffraction propagation distances and beam widths of Airy optical beams.

In this work, we circumvent the above-mentioned limitations of the present metasurface-based Airy optical beam generators and realize long working and non-diffraction propagation distances, narrow beam-width Airy optical beam with a synthetic metasurface that combines a cubic phase and the phase of a Fresnel holographic lens. Such a synthetic metasurface allows flexible control over the working distance of the Airy beam generator (up to 144 μm, i.e. ~262λ, from the metasurface) by adjusting the focal plane of the Fresnel holographic lens meanwhile retaining a long non-diffraction propagation distance of up to 120 μm (~3.5λ) over the spectral range from 550 nm to 710 nm. Furthermore, we demonstrate an array of 1×4 Airy optical beams by superimposing the phase of an optimized Dammann grating onto the synthetic metasurface. And each beam in the array has similar optical properties as the aforementioned individual one.

2. Simulations and experimental measurements

2.1. Design model

To generate the single 2D Airy beam, we add the cubic phase and the phase of a Fresnel holographic lens together into a single synthetic metasurface phase, which is expressed mathematically as follows:

\[
\Phi(x_{\text{META}}, y_{\text{META}}) = \frac{1}{3} (2\pi b_2) (x_{\text{META}}^3 + y_{\text{META}}^3) - \frac{\pi}{f} (x_{\text{META}}^2 + y_{\text{META}}^2)
\]

(1)

where \( f \) is the focal length of the Fresnel holographic lens and \( b_2 = \frac{\pi}{4f} \) with \( b_0 \) being a half width of the main lobe. The phase profile described by Equation (1) can be realized with a single all-dielectric synthetic metasurface, which is much more compact than conventional Airy-beam generation systems typically combining a physical lens as a Fourier transform component and a SLM with a cubic phase distribution. At the focal plane of the synthetic metasurface (the same as that of the Fresnel holographic lens), a circularly polarized incident beam passing through the metasurface is converted to an Airy optical beam with inverse circular polarization.

In addition, we show that adding the phase profile of a one-dimensional (1D) Dammann grating together with the phase profile of a single Airy beam gives rise to the phase mapping for generation of a 1×4 Airy beam array. The phase profile is given by:

\[
\Phi(x, y) = \frac{1}{3} (2\pi b_2) (x^3 + y^3) - \frac{\pi}{f} (x^2 + y^2) + \phi_{\text{DG}}(x)
\]

(2)

where \( \phi_{\text{DG}} \) is the phase of the 1D Dammann grating.
2.2. Experimental measurement of a single 2D Airy optical beam

The experimental measurement results of the generated single 2D Airy beam are presented in Figure 1. Figure 1a shows the longitudinal field pattern of the 2D Airy beam, which is extracted from a reconstructed three-dimensional (3D) field pattern based on the recorded magnified transverse field pattern slices on each discrete longitudinal positions along the incident beam propagation direction. We preset $b_1 = 0.0143$ for the cubic phase profile and the focal length of the Fresnel holographic lens phase included in the metasurface (i.e. the working distance of the metasurface) to be 144 μm at the design wavelength $\lambda_d = 630$ nm. It is demonstrated in Figure 1a that the measured propagation trajectory coincides with the theoretical pre-defined trajectory of the main lobe marked with blue dash line, which is analytically expressed as $x = \frac{2z^2}{6d(f+z)}$. Figures 1b-d show the transverse $xy$ field distributions at various longitudinal positions of $z = 55$ μm, 0 μm and -30 μm. The field profiles in Figures 1e-g are extracted from the white dashed lines in Figures 1b-d.

![Figure 1](image1.png)

Figure 1: a) Experimentally reconstructed longitudinal field pattern of the 2D Airy beam at the wavelength $\lambda_d = 630$ nm. Recorded transverse field distributions at various longitudinal positions of $z = 55$ μm b), 0 μm c) and -30 μm d).

2.3. Experimental measurement of an array of 2D Airy optical beams

Herein, we purposely optimize the phase of the Dammann grating encoded with specific binary phase distribution, composed of $1 \times 6$ super-cells with a cell pitch size of 48 × 8 μm, in order to achieve a high quality beam array. Each super-cell consists of 192 × 32 rotating nanorods with a spacing of 250 nm. We preset $b_1 = 0.0228$ for the cubic phase profile and the focal length of the Fresnel holographic lens phase included in the metasurface (i.e. the working distance of the metasurface) to be 78.8 μm at the design wavelength $\lambda_d = 630$ nm. Figure 2a shows the simulated longitudinal field distribution for the array of $1 \times 4$ 2D Airy optical beams. Figure 2b explores the experimentally measured longitudinal field distribution, which matches well with the simulated result in Figure 2a. It is found that the measured average FWHM of the four mainlobes of the array is 2.22 μm, while FDTD simulated value is 2.08 μm, both of which are close to the theoretical value of 2.26 μm. Figures 2c and d exhibit and compare the simulated and experimental transverse field distributions marked with the white dash lines in Figures 2a and b. It is obviously shown in Figures 2c and d that the field patterns of these four 2D Airy optical beams are homogenous.

![Figure 2](image2.png)

Figure 2: Simulated a) and experimentally measured b) longitudinal field distributions of the array of $1 \times 4$ 2D Airy optical beams at the wavelength $\lambda_d = 630$ nm. Simulated c) and measured d) transverse field patterns at the vertical position of $z = 4$ μm marked with the white dash lines in a) and b).

3. Conclusions

In conclusion, we have experimentally demonstrated that a strategy for generating broadband, long working and non-diffraction propagation distances, and high resolution Airy beams and beam arrays based on dielectric metasurfaces. Unlike the previous investigations which usually consider both amplitude and phase manipulations limiting available unit elements, pure phase manipulation enables direct phase additions of the cubic phase and the phase of a holographic Fresnel lens applied to the metasurface. Our work will open up an avenue for wider applications of Airy beams and beam arrays, especially for high-resolution optical imaging, optical tweezing with large penetration depths in live samples, as well as in the fields of parallel processing, for example, parallel laser printing and etc.

Acknowledgements

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References


Two superior photodetectors empowered by Al metasurfaces and hybrid plasmonic structures

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In this talk, I introduce two superior photodetectors in visible and ultraviolet regimes, respectively. The first photodetector is an ultrasensitive gateless photodetector based on 2D bilayer MoS₂-1D Si nanowire-0D Ag nanoparticle hybrid structure. Such a hybrid structure shows a gateless responsivity of 402.4 A/W at a wavelength of 532 nm, which represents the highest value among the reported gateless plasmonic MoS₂ photodetector. Its great responsivity and large active area results in an exceptional detectivity of 2.34×10¹² Jones. This study provides a new approach for designing high performance 2D TMDC-based optoelectronic devices. The second photodetector is Al plasmonics enriched ultraviolet GaN photodetector with ultrahigh responsivity, detectivity, and broad bandwidth. By deliberately designing a periodic nanohole array in this Al film, we enabled localized surface plasmon resonance and extraordinary transmission, and thereby obtained the maximum responsivity (670 A/W) and highest detectivity (1.48 × 10¹⁵ cm-Hz¹/₂-W⁻¹) at the resonance wavelength of 355 nm. To our best knowledge, the presented detectivity is the highest compared with those of other reported GaN photodetectors.

References
Chirality, magnetism, and magnetoelectricity: Separate phenomena and joint effects in metamaterial structures
Antiferromagnetism, chirality, and magneto-optical effects

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Abstract

The chirality of magnetization, associated with canting of neighboring pairs of spins away from a collinear arrangement occurring in magnetic materials has been a subject of intensive research since several decades. While the breaking of crystal symmetry of magnets gives rise to such phenomena as the crystal Hall effect \cite{1} and Dzyaloshinskii-Moriya interaction, imprinting chirality in the spin system can also result in symmetry breaking and emergence of novel phenomena \cite{2}. This particularly concerns the realm of transport effects, where for example the existence of chiral orbital magnetism and chiral Hall effect emerging in non-collinear textures has been recently demonstrated \cite{3,4}. Inspired by latter works, which predict the chirality-sensitive contributions to magneto-transport in skyrmions and domain walls, we study the influence of chirality on Hall effects and magneto-optical phenomena in frustrated magnets. By referring to models, symmetry arguments and first principles calculations we suggest a way to identify the sense of crystal and magnetic chirality of two-dimensional magnets from the behavior of the Hall and magneto-optical effects that they exhibit, thereby promoting new protocols for probing these fundamental properties of matter.

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Spin current generation due to Stern-Gerlach-like effects

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Abstract
Spin current is a key concept in spintronics. It is known that the spin current is generated in media with the presence of spin dependent potentials, such as a strong spin-orbit coupling \cite{1-4} and spin-vorticity coupling \cite{5-7}. In particular, the gradient of effective magnetic fields is utilized in \cite{4-7}. The effective magnetic fields are created by the inhomogeneous spin-orbit coupling \cite{4}, or by spin-vorticity coupling \cite{5-7}. That is, a variety of the Stern-Gerlach-like effects are exploited for generating spin currents. Recently, we proposed a new mechanism of spin-current generation by the Stern-Gerlach-like effect where the effective magnetic field originates from the transverse spin \cite{8-10} of the surface plasmon polariton (SPP) in a non-magnetic meta \cite{11,12}.

In this talk, we focus on the Stern-Gerlach-like spin transport phenomena driven by spin-vorticity coupling in elastic materials \cite{6} (Fig.1) as well as by the transverse spin of the SPP \cite{11,12} (Fig.2).

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure1.png}
\caption{Spin current generation by spin-vorticity coupling. When a Rayleigh-type surface acoustic wave is injected to an elastic material, spin current is created along the vorticity gradient.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure2.png}
\caption{Spin current generation by the transverse spin of the SPP.}
\end{figure}

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Generation of superconducting vortices by angular momentum of light

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Abstract
We investigate a superconducting state irradiated by a laser beam with spin and orbital angular momentum. It is shown that superconducting vortices are generated by the laser beam due to heating effect and transfer of angular momentum of light. Possible experiments to verify our prediction are also discussed.

References
Chirality of Multipolar Lattice Resonances in Plasmonic Crystal Excited by Vortex Beams

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Abstract
We demonstrate that dipolar and quadrupolar lattice resonances in finite-sized, square-lattice arrays of metal nanodisks can be excited by circularly polarized vortex beams carrying spin and orbital angular momenta. The simulation results show that spatial distributions of the lattice resonances in the plasmonic crystals exhibit characteristic patterns with the chirality that conserve the chirality of the incident light and the excited plasmonic fields of individual nanodisks.

1. Introduction
The Laguerre-Gaussian beam, called as optical vortex, that possesses helical wave-front and doughnut beam profile has attracted significant attention because of the unique characteristics of carrying the orbital angular momentum in addition to the spin angular momentum corresponding to circular polarization. We demonstrated that multipolar plasmons of metal nanodisks can be selectively excited by circularly polarized vortex beams [1]. The orbital and spin angular momenta are transferred from vortex photons to localized plasmons. This plasmonic field localized by the nanodisk corresponds to the whispering gallery mode (WGM), where the angular mode number is determined by the total angular momentum of the vortex beam. Unfortunately, the coupling from vortex photons to multipolar plasmons is with low efficiency (<10%), because the size of metal disk determined by the WGM resonance is smaller than the diffraction-limited beam spot size.

In order to increase the coupling efficiency, we employed the lattice resonances in periodic metal nanoparticles, i.e., plasmonic crystal, in which collective resonances are mediated by the diffractive coupling of localized plasmons [2]. In this presentation, we theoretically demonstrate that the dipolar and quadrupolar lattice resonances in square lattice plasmonic crystals composed of nanodisks can be excited by a normally incident, circularly polarized vortex beam. The spatial distributions of the lattice resonances in the plasmonic crystals exhibit characteristic patterns where the chirality of the spatial patterns conserves the chirality of the incident structured light and the excited plasmonic fields in the individual nanodisks [3].

2. Results and discussion
Figure 1 shows the model used in the following calculations. For simplicity, we consider a square lattice plasmonic crystal in a homogeneous background with a refractive index of n = 1.0. The structure consists of 9 x 9 array of gold disks with diameter of 380 nm and thickness of 30 nm. The lattice period (L = 470 nm) is set such that a normally incident, circularly polarized vortex beam shown in the inset of Fig. 1 can excite both dipolar and quadrupolar lattice resonances.

Figure 1. Square lattice plasmonic crystal consisting of 9 x 9 gold nanodisks. The inset shows the cross-section of incident vortex beam. The arrows indicate the electric field vectors.

First, we calculated the extinction spectrum of the plasmonic crystal structure. The spectrum exhibits a dipolar peak at 1500 nm and quadrupolar peak at 900 nm. When the vortex beam with the wavelength of 900 nm is used as the excitation light (Fig. 2(a)), the quadrupolar plasmon modes are excited in the individual nanodisks (subfigure of Fig. 2(b)). The overall intensity distribution of the plasmonic crystal, i.e., crystal mode, has the Gaussian-like profile with...
the intensity maximum at the center (Fig. 2(b)), even though the incident beam has the ring-shaped intensity profile. This result indicates that the plasmonic resonances of individual nanodisks are interacted with each other and collectively oscillated so that the resonances are propagated and concentrated from the peripheral disks to the central disks. In this case, the chirality of the incident vortex photon is transferred to the individual disk mode not to the crystal mode. When the wavelength of the vortex beam is set to 1500 nm at the dipolar resonance, the overall distribution has the doughnuts shape and the individual disks exhibit dipolar resonances with the rotational phase depending on the azimuthal angle (Fig. 2(c)). In contrast to Fig. 2(b), the chirality of the vortex photon is transferred to the crystal mode not to the individual disk mode. It should be noted that in the both cases of dipolar and quadrupolar resonance wavelengths (Figs. 2(b), 2(c)), the total angular momentum is conserved when the incident vortex mode is transferred to the individual disk multipolar mode and the plasmonic crystal mode.

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References

Universal energy barriers of large magnetic skyrmions

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Abstract
Magnetic skyrmions are whirls in the magnetization for which a topological winding number can be defined. Because of this topology, skyrmions are often believed to gain some superior topological protection, in particular close to the energy barrier above which can only be violated for a large class of systems. Moreover, the height of the barrier is determined by higher order gradients of the continuum theory which arise, e.g., from higher order interactions.

1. Introduction
Magnetic skyrmions combine a number of features that make them very interesting for potential application in information technology devices: they are available at various sizes with diameters down to the nanometer scale, they can be stabilized at room temperature, and they can be manipulated by spin-torques and other external stimuli [1]. The maybe most fascinating feature is, however, their real-space topology. The magnetization \( \hat{n}(r) \in S^2 \) in a skyrmion covers the whole parameter space such that the winding number

\[
Q = \frac{1}{4\pi} \int \hat{n} \cdot \left( \frac{d\hat{n}}{dx} \times \frac{d\hat{n}}{dy} \right) \, dr \in \mathbb{Z}
\]

(1)

for a skyrmion in a ferromagnetic background with \( \hat{n}(r) = \hat{z} \) evaluates to \( Q = -1 \).

2. The myth of infinitely high barriers
When creating or annihilating a skyrmion, i.e., when transferring the system to a fully polarized state with \( Q = 0 \), the discrete winding number jumps as \( \Delta Q = 1 \) which can only occur via an intermediate discontinuous magnetization texture (except at the edges of the sample where the magnetization is discontinuous by definition). Such a discontinuous vortex texture, however, is energetically very unfavorable as a vortex of radius \( R_v \) on an atomic lattice with lattice constant \( a \) yields a contribution to the magnetic stiffness which diverges as \( \ln(R_v/a) \) in the continuum limit where \( a \rightarrow 0 \). It is therefore often believed that the stabilizing energy barrier for a skyrmion also diverges in the continuum limit, giving skyrmions absolute stability.

While this argument is not strictly true on a discrete lattice, it also neglects the fact there are other ways to create a skyrmion. Decay paths which involve a singularity might, in fact, be blocked by the diverging barrier, but the possibility of shrinking the skyrmion until it effectively vanishes remains an open option as we showed recently [2]. For a simple toy model with only nearest neighbor exchange and Dzyaloshinskii-Moriya interactions we showed that the energy barrier asymptotically becomes

\[
\delta E_{sw} \approx 4\pi J - 3^{2/3} 8\pi ( -\bar{K}_4 )^{1/3} J
\]

(2)

for large skyrmions, where \( J \) is the effective magnetic stiffness in the continuum approximation. A necessary condition is, however, that the energy of the fourth order gradient terms \( K_4 \) of the effective continuum model has a negative sign. In a system with only nearest neighbor interactions this is naturally the case and \( \bar{K}_4 = -\frac{\partial^2}{\partial x^2 \partial y^2} \), where \( \xi \) is the magnetic length scale, \( a \) the lattice constant, and \( D \) the effective continuum DMI. In the true continuum limit \( a \rightarrow 0 \), the barrier therefore becomes \( 4\pi J \).

3. Conclusions
In our publication Ref. [2] we derived an analytic approximation for the finite energy barrier of large magnetic skyrmions in two-dimensional chiral magnets. However, our solution requires that \( K_4 < 0 \) which can be violated as next-nearest neighbor interactions and also higher order interactions are included, as for example by Paul et al. [3]. We also discussed this scenario in our publication, as well as systems where skyrmions are purely stabilized by frustrated interactions and without asymmetric DMI, which requires a mixed continuum/discrete ansatz but also confirms finite energy barriers, all in agreement with numerical minimal energy path calculations.

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Synthetic chiral light for efficient control of chiral light matter interaction

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Abstract

I will talk about synthetic chiral light, a new type of freely propagating optical fields that we have recently introduced [1]. Synthetic chiral light enables the highest possible degree of control over chiral light-matter interaction. It allows us to drive a strong nonlinear response in chiral molecules of a selected handedness. As a result, we can force a particular molecular enantiomer to emit bright harmonic light while its mirror twin remains dark, reaching the ultimate efficiency limit in chiral discrimination.

1. Introduction

Light is one of the most powerful and precise tools allowing us to control, shape and create new phases of matter. In these tasks, the magnetic component of a light wave has so far played a unique role in defining the wave’s helicity, but it weakly influences the optical response of matter. Chiral molecules offer a typical example where the weakness of magnetic interactions hampers our ability to control the strength of their chiro-optical response, limiting it several orders of magnitude below the full potential. Indeed, chiral response in standard optical techniques (e.g. photo-absorption circular dichroism [2]) is only possible outside the dipole approximation. Weak non-dipole interactions lead to, in general, weak chiro-optical responses and a justified impression that chiral discrimination is hard, especially on ultrafast time scales.

2. Synthetic chiral light

We have recently shown that freely propagating optical fields can be made chiral already in the dipole approximation [1]: we have introduced synthetic chiral light, a new type of freely-propagating optical fields in which the tip of the electric field vector draws a chiral, three-dimensional Lissajous curve in time, at each fixed point in space (Fig. 1a). Such light is locally chiral: unlike circularly polarized light, its chirality does not rely on the spatial helix of the light field. Thus, it remains chiral in the dipole approximation. Here I will show how to generate such light practically using non-collinear optical setups (Fig. 1a), how to characterize and control its handedness, and how to maintain it globally, across the entire interaction region.

Synthetic chiral light enables the highest possible degree of control over the enantio-sensitive nonlinear optical response of chiral matter at the level of total signal intensities. We have demonstrated complete discrimination between randomly oriented left- and right-handed molecules using high harmonic generation as a nonlinear probe of ultrafast chiral dynamics [1]. Our work shows that we can fully quench high harmonic emission from a desired enantiomer while enhancing it in its mirror twin (Figs. 1b,c), reaching the ultimate efficiency limit in chiral discrimination: 200% of chiral dichroism. This giant chiroptical response is fully controlled by the incident light. Moreover, it is completely background-free, separated from the standard achiral signal in frequency, polarization and space. Synthetic chiral light opens efficient ways for controlling chiral matter and for ultrafast imaging of chiral dynamics in gases, liquids and solids.

References

Fig. 1. a) Setup for generating synthetic light that is *locally* and *globally* chiral [6]. It includes two non-collinear laser beams, each carrying a strong $\omega$ field and a weak, orthogonally polarized, $2\omega$ field. In the focus, the total $\omega$ field is elliptical in the xy plane, the $2\omega$ field is linear along z. Upper inset: three-dimensional, chiral Lissajous curve of the field in the focus. b) Harmonic intensity for randomly oriented R and S propylene oxide molecules resolved in emission angle (divergence), for the field parameters $\lambda = 1.77\mu m$, $I_\omega = 1.3 \cdot 10^{13} W cm^{-2}$, $I_{2\omega} = 0.01 \cdot I_{2\omega}$, $\phi_{\omega,2\omega} = 0$, pulse duration 23 fsec at constant intensity, $\alpha = 5^\circ$, and focal diameter 400$\mu$m. Shifting $\phi_{\omega,2\omega}$ by $\pi$ reverses the field’s handedness, it is equivalent to exchanging the enantiomer. c) Total angle-integrated even harmonic intensity and chiral dichroism, $CD = 2(I_R - I_S)/(I_R + I_S)$. 
Optical vortex induced structured materials via two-photon-absorption

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Abstract
We report on that irradiation of picosecond optical vortex pulses with orbital angular momentum allows us to form various unique (helical or flower-shaped) structures via two photon absorption. Such structures reflect not only the spatial intensity profile, wavefront and polarization of the irradiated optical vortex field but also the nonlinear spatial modulational instability of optical vortex in materials. Such structured materials may provide us new important physical insights for future studies of nonlinear interaction between light fields with OAM and materials.

1. Introduction
Optical vortex light field possesses an orbital angular momentum (OAM) and a ring-shaped spatial form, associated from its helical wavefront \cite{1,2}. In recent years, we and our co-workers discovered that an optical vortex field allows the orbital motion of the irradiated materials, such as metals, semiconductors, and even liquid-phase resin, to form nano/micro-scale helical structures \cite{3-6}.

Azo-polymers exhibit photo-induced mass transport originating from an optical gradient force, anisotropic photofluidity, and trans-cis photo-isomerization, thereby enabling the formation of photo-induced reversible reliefs, reflecting the spatial intensity profile and polarization of the irradiated light \cite{7,8}. Thus, they provide a myriad of applications, for instance, the development of rewritable optical circuits, and rewritable optical data storages. The optical vortex also twists azo-polymers to form a single-arm helical relief with the aid of the spin angular momentum (SAM) originated from with the helical electric field of the circular polarization \cite{9,10}.

Such optical vortex induced helical structures will offer the development of chiral metamaterials for highly sensitive detection and reaction of chiral chemical composites.

Nonlinear interactions between optical light field and materials further offer new fundamental and applied sciences: for instance, two-photon-absorption (TPA) enables the 3-dimensional microfabrication of materials to realize high-density optical data storage with high spatial resolution beyond the diffraction limit \cite{11}.

Thus, optical vortex induced TPA will provide not only the helical structures of materials with a freedom of OAM, but also entirely new nonlinear optical phenomena, such as an OAM conservation law in TPA, and SAM-OAM coupling in TPA.

In this presentation, we introduce TPA-induced structured materials formed by irradiation of near-infrared picosecond optical vortex pulses.

For instance, the TPA-induced photoisomerization in azo-polymers enables us to form helical relief with high longitudinal and transverse spatial resolution, \textit{i.e.}, without any undesired Airy rings and only within an extremely narrow defocusing tolerance. Such TPA-induced helical mass-transport will lead to the development of high-density optical data storage with the freedom of OAM.

TPA-induced photopolymerization also offers a flower-shaped relief with petals along an azimuthal direction, manifesting the spatial modulational instability associated with nonlinear light-matter interaction in the azo-polymer film rather than the spatial intensity profile and wavefront of the irradiated optical vortex. These will offer entirely new fundamental physical insights for the interaction between OAM and materials.

Figure shows the fabricated reliefs via TPA photoisomerization in azo-polymers by irradiation of picosecond optical vortex pulses.

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Figure 1: (a) 2D and 3D helical reliefs of azo-polymers formed by irradiation of picosecond optical vortex pulses with low power. (b) High power picosecond optical vortex pulses create a flower-shaped relief with two petals.

References

Theory of Photo-Induced Spin Polarization in Spin-Orbit-Coupled Systems

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Abstract
We theoretically study the photo-induction of spin polarization in spin-orbit coupled electron systems both numerically with a time-dependent Schrödinger equation and analytically with the Floquet theorem. It is demonstrated that a rotating electric-field component of circularly polarized light is converted to an effective static magnetic field by the spin-orbit interaction and induces the spin polarization perpendicular to the light-polarization plane. We find that the magnitude and sign of the induced spin polarization are governed by momentum dependence of the effective magnetic field and the Fermi-surface geometry, which enables us to design the magneto-optical responses of materials.

1. Introduction

Optical control of electron spins in solids has been an attracting issue in condensed matter physics. In this proceedings, we report our theoretical demonstration that a rotating electric-field component of incident circularly polarized light (instead of its rotating magnetic-field component) can induce spin polarization efficiently in electron systems with static magnetic field. We find that the effective magnetic field has remarkable momentum dependence and, thereby, the geometry of Fermi surface governs the magnitude and sign of the induced spin polarization.

2. Simulations and Formulations

We start with a time-dependent Hamiltonian on the square lattice \( H(\tau) = H_0(\tau) + H_{\text{so}}(\tau) \) with

\[
H_0(\tau) = 2t \sum_{k,\sigma} \left[ \cos(k_x + A_x) + \cos(k_y + A_y) \right] c_{k,\sigma}^\dagger c_{k,\sigma}
\]

\[
H_{\text{so}}(\tau) = -\alpha_D \sum_k \left[ \sin(k_x + A_x) c_{k,\sigma}^\dagger \sigma_{\sigma'} c_{k,\sigma'} \right. \\
\left. - \sin(k_y + A_y) c_{k,\sigma} c_{k,\sigma'} \right].
\]

The first (second) term describes the kinetic energies (the Dresselhaus spin-orbit interactions). Here the effect of photo-excitation is taken into account through the time-dependent vector potential \( A(\tau) = -\int_0^\tau E(\tau')d\tau' \). The rotating light electric field is given by \( E(\tau) = E_0 \beta(\tau)(\cos \omega \tau, \sin \omega \tau) \) with amplitude \( E_0 \) and angular frequency \( \omega \). Table 1 gives unit conversions for \( \omega, E_0, \) and time \( \tau \) when \( \omega = 1 \text{ eV} \) and \( a = 5 \text{ Å} \), which are typical values for semiconductors. The factor \( \beta(\tau) = 1 - e^{-\tau^2/\sigma^2} \) is introduced to mimic the adiabatic application of light field.

The matrix representation of \( H(\tau) \) is given by

\[
H(\tau) = \sum_k \begin{pmatrix} \epsilon_{k,\sigma} & \gamma_{k,A} \\ \gamma_{k,A}^* & \epsilon_{k,A} \end{pmatrix} \begin{pmatrix} c_{k,\sigma} \cr c_{k,\sigma'} \end{pmatrix},
\]

where \( \gamma_{k,A} = -\alpha_D \left[ \sin(k_x + A_x) + i \sin(k_y + A_y) \right] \).

Time evolution of the system is calculated by solving a discretized equation,

\[
|\Psi_{k,\nu}(\tau + \Delta \tau)| = \exp[-i \Delta \tau H(\tau + \Delta \tau/2)] |\Psi_{k,\nu}(\tau)|.
\]

Here \( |\Psi_{k,\nu}(\tau)| \) is the \( \nu \)th (\( \nu = 1, 2 \)) one-particle state with a wave vector \( k \).
In contrast, the out-of-plane spin component and total spin, respectively, in which the spin orientations at several points on the Fermi surfaces are indicated by arrows. 

In Fig. 1(b), we display the energy dispersion relations for electron fillings of (a) $n_a=0.92105$ and (b) $n_a=0.20005$ when $\alpha_D=0.1$, $E_0=1$. The Fermi surfaces for $n_a=0.92105$ and $n_a=0.20005$ are shown in Figs. 1(c) and (d), respectively, in which the spin orientations at several points on the Fermi surfaces are indicated by arrows.

In Figs. 2(a) and 2(b), we show simulated time evolutions of total spin $S=(S_x, S_y, S_z)$ for electron fillings of (a) $n_a=0.92105$ and (b) $n_a=0.20005$ when $\alpha_D=0.1$, $n_c=0.20005$. The in-plane spin components $S_x$ and $S_y$ show sinusoidal oscillations around zero. In contrast, the out-of-plane spin component $S_z$ exhibits saturation, indicating that the spin polarization appears perpendicular to the plane. Noticeably, its magnitude and sign are distinct between the two cases, that is, it is negative for $n_a=0.92105$, whereas positive for $n_a=0.20005$.

The observed filling-dependence of spin polarization can be understood by the Floquet theory. In the high-frequency limit, the effective Floquet Hamiltonian $H_{\text{eff}}$ is given by $H_{\text{eff}}=H_0-\hbar [H_1, H_{-1}]$ with $H_0=\sum_k (c_k^\dagger c_k^\dagger e^{i\omega t})$ and $H_1=\sum_k (\tilde{\epsilon}_{k,A} + \tilde{\gamma}_{k,A} + h_{\text{eff}})(c_k^\dagger c_k)$, where

$$H_{\text{eff}} = \frac{\sigma_D E_0}{\omega^3} \cos(k_x) \cos(k_y).$$

Equation (6) means that the circularly polarized light effectively gives rise to a momentum-dependent static magnetic field, $h_{\text{eff}}$, perpendicular to the light-polarization plane. In Figs. 2(c) and (d), the $k$-dependence of $h_{\text{eff}}$ and the Fermi surfaces are depicted. For the higher electron filling of $n_a=0.92105$, the two Fermi surfaces are located in the region where $h_{\text{eff}}$ is positive, which gives negative spin polarization $S_z < 0$. On the contrary, for the lower electron filling of $n_a=0.20005$, the two Fermi surfaces are located in the region where $h_{\text{eff}}$ is negative, which gives positive spin polarization $S_z > 0$. In this way, the magnitude and sign of spin polarization $S_z$ are determined by the momentum dependence of $h_{\text{eff}}$ and the Fermi-surface geometry. Our numerical simulations also revealed that the magnitude of spin polarization is proportional to $E_0^2/\omega^3$, which is ascribed to the relationship $h_{\text{eff}} \propto E_0^2/\omega^3$ in Eq. (6).

4. Conclusion

We theoretically demonstrated that the rotating electric field of circularly polarized light efficiently induces the spin polarization in the spin-orbit-coupled electron systems. The sign and magnitude of the photo-induced spin polarization sensitively depend on the electron filling and the Fermi-surface geometry. These findings pave a new way to design the magneto-optical responses of materials.

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References


Magnon-polaritons condensates

with superfluidity and vortex formation

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Abstract

The avoided crossing modes arising from the strong coupling between photons and dipole-carrying excitations of a material are well known as a polariton. The situation when dipole-carrying excitations are in a high-quality resonator, dramatically changes the behavior. In a case of exciton-polaritons, it leads to sustained trapping of the emitted photon. Such strong-coupling modes can appear as composite bosons with the spontaneous formation of quantized vortices in the condensed phase of a polariton fluid. We show that magnon-polaritons can be realized due to magnon condensation caused by magnetic dipole-dipole interaction. We study quantized vortices in magnon-polariton condensates arising from magnetic-dipolar-mode (MDM) oscillations in a quasi-2D ferrite disk placed in a microwave cavity. We show that is possible to trap a magnon Bose-Einstein condensate in a ring geometry and induce rotational superflow in this system. We have a spinor dipolar BEC. We observe a persistent current in spinor condensates. A spinor transforms to its negative when the space is continuously rotated through a complete turn from 0° to 360°. Electric dipoles in a YIG disk are described by a vector order parameter and therefore exhibits spontaneous symmetry breaking. Such a "magnetic ordering" is exhibited as a spinor Bose–Einstein condensate. We consider torque transfer induced by MDM oscillations. The resulting configurations show transfer between spin and orbital angular momentum in the form of Einstein-de Hass effect, and novel topological properties. We propose the concept of using magnetoelectric (ME) vortices as topologically stable microwave-signal carriers in long-range ordered dielectric materials.
Realization of Dynamic Electromagnonic Microwave Crystal via Magnon-Photon Coupling in Artificial Multiferroic Heterostructure

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Abstract
Magnon transport in time-dependent periodic spatial potentials—dynamic magnonic crystals—paves a way to energy-efficient data transfer and information processing. Voltage control of magnon currents promises to be fast and low energy-consuming. It can be achieved in artificial multiferroic heterostructures, where the strong coupling of magnons and microwave photons constitutes new quasiparticles called electromagnons. Here, we report on the experimental realization of a voltage-controlled dynamic electromagnonic crystal operating at microwave frequencies.

1. Introduction
Magnon spintronics concerned with structures, devices and circuits that use spin currents carried by quanta of spin waves (SW)—magnons—for data transfer and processing. One of the main challenges for magnonic circuits is SW propagation control. Such control can be realized by magnonic crystals [1]. To date, dynamic manipulation of the magnonic crystals was achieved with current [2, 3] and optic [4] control influence. At the same time, voltage control promises to be faster and lower energy consuming [5, 6, 7, 8]. One of the ways to control magnon currents with voltage (or electric field) is to use coupling between magnons and microwave photons in periodic ferroelectric (multiferroic) heterostructures called dynamic electromagnonic crystals (DEMC).

2. Experiment
The proposed DEMC and the measurement cell are shown in Fig. 1. The artificial multiferroic heterostructure, which is composed of the rectangular barium strontium titanate (BST) slab and yttrium iron garnet (YIG) film, constitutes the basis for one-dimensional DEMC (Fig. 1a). The experimental prototype of the DEMC is a part of the YIG film-based spin-wave waveguide contacted with the BST slab surface having a “transparent” metal grid electrode. The prototype utilizes 1 mm-thick and 8 mm-long BST slab as well as 9.1 μm-thick and 40 mm-long YIG film. The grid electrode consists of 10 100 nm-thick and 60-μm-wide stripes. The period of the grid Λ is 750 μm. The measurement cell is fabricated in the form of a phase shifter (Fig. 1a). The YIG film is longer than the BST slab in order to provide the possibility for the efficient excitation and reception of spin waves by the 50 μm-wide and 2 mm-long short-circuited microstrip antennas. The YIG film waveguide is positioned over the antennas and fixed to contact them. A spatially uniform magnetizing field \( H = 2106 \text{ Oe} \) is applied across the YIG waveguide along the antennas and grid electrodes providing the conditions for excitation and reception of surface spin waves (see, e.g. Ref. [3]).

The physical mechanism underlying the control of the DEMC band gaps can be understood as follows. Initially, the multiferroic heterostructure without application of the control voltage represents a spatially homogeneous waveguide for spin-electromagnetic waves (SEWs) [9]. Therefore, the electromagnon currents flow without backscattering as in a regular waveguide. An application of voltage to the grid electrode creates a spatially periodic bias electric field across the BST slab (see Fig. 1b). This field causes the spatial periodicity of the polarization and of the value of dielectric permittivity of the BST slab. Under these conditions, initially excited SEWs having the Bragg wave vector \( k = n \pi / \Lambda \) are coupled with the waves propagating in the opposite direction forming the electromagnonic band gaps at corresponding frequencies (Fig. 2a). Therefore, the periodic polarization of the BST slab leads to the periodic change in the wave-guiding properties of the YIG-BST heterostructure and provides the rejection gap in the amplitude-frequency characteristic of the investigated DEMC (Figs. 2b,c). Removal of the bias voltage transforms the DEMC back to a spatially homogeneous multiferroic SW waveguide.

The SEWs propagating in the DEMC are formed because of coupling of the surface SW mode (localized mostly in the magnetic film) with electromagnetic wave mode TE1 (localized mostly in the ferroelectric slab). A detailed analysis shows that a strong coupling between the magnons and microwave photons takes place around the point of cross-
Figure 1: (a) A measurement cell. (b) Sketch of a cross section of the voltage-controlled dynamic electromagnonic crystal (DEMC).

Figure 2: (a) Dispersion branch of the spin-electromagnetic wave (SEW) in the electromagnonic crystal shown in Fig. 1a. Two band gaps, BG_1 and BG_2, are formed below the spin-wave cut-off frequency \( \omega_M/(2\pi) \) and one band gap, BG_3, above it. (b) Dispersion curves of SEWs (solid red curve) and pure spin waves (dash-dotted green curve) calculated for \( U = 1800 \) V. (c) Transmission characteristic of the DEMC measured for the applied voltage \( U = 1800 \) V. The electromagnonic rejection gap (EMRG) formed at the band gap BG_3 is clearly visible. Inset shows the EMRG for three different voltages.

3. Discussion

Note that the realization of the voltage control of the perpendicular magnetic anisotropy in the reconfigurable magnonic crystals [8] and in the logic devices [6] requires to produce an electric field of 100-500 V/\( \mu \)m. In contrast, the presented here DEMC requires only 1.8 V/\( \mu \)m. Moreover, the numerical estimations show that a miniaturization of the DEMC structure to micrometer scale will reduce the control voltage down to 1.8 V.

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References

The role of plasmonic excitations in the far-field configurational chirality

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Abstract

Broken mirror symmetry of chiral structures imposes a lack of mirror symmetry in the scattering profile. When an energy dissipation channel is introduced in the system, an overall optical activity arises. Plasmonic nanostructures, therefore, are ideal platform to induce optical activity by means of constitutional or configurational chirality. We experimentally investigate mechanism of the plasmonically-induced configurational chirality in a periodic monoclinic hole array with a broken mirror symmetry. The resulting optical activity of the structure is studied by use of k-space leakage radiation measurements.

1. Introduction

Chirality is a geometrical property referring to objects with the lack of mirror symmetry. Chiral nano-particles are known to exhibit optical activity that is to induce a different optical response for illumination of circularly polarized light with different handedness. Excitation of collective charge oscillation in the vicinity of a metal dielectric interface (surface plasmon SPs) enhances these interactions. Compared with the weak optical activity of the natural chiral media, carefully engineered chiral metamaterials exhibit almost an order of magnitude stronger effects, thus making nanostructures highly promising in a variety of plasmonics application such as sub diffraction imaging[1],[2], EM cloaking[3][4] and negative refraction[5]. Recently, a lot of an effort has been focused on the polarization sensitive asymmetric transmission effect in metamaterials[6] where the partial inter-conversion of the incident light’s circular components is asymmetric with respect to the propagation directions [7]. In plasmonics a 3D metamaterial is replaced by a 2D periodically arranged (unit cells) structure in a conducting thin layer – a “metasurface”. This periodic structure exhibits a collective behavior, which is fundamentally different from the bulk material. Chiral unit cells show cross-coupling between the electric and magnetic fields of the light at their resonance frequency; therefore, RCP and LCP light encounter different transmissions. This leads to the polarization tuning of the incident light. Recent wide interest in chiral metasurfaces has led to investigation of a large portfolio of unit-cells designs, from the famous gammadion shaped meta-atoms[8] to split -rings[9] fish scales shapes L-shapes[7] and extrinsically chiral structures[10] that spanned the frequencies from the visible to the gigahertz (GHz) range. One of the main aims of the optimized metasurface is to achieve the strongest polarization state discrimination which is crucial for nanophotonics. This is achieved due to the circular birefringence of the unit-cells resulting in two effects - the optical rotation dispersion (ORD) – wavelength dependent rotation of the polarization ellipse primary axis; and the circular dichroism (CD) – the ellipticity angle.

In this letter we experimentally investigate the role of the plasmonic excitation in optical activity of metasutures with a configurational chirality. Our structure was a grating of cylindrical hole arranged in a monoclinic unit cells with broken mirror symmetry, fabricated on gold (Au) thin film. We investigate the CD distribution in the k-space by utilization of a leakage radiation microscopy (LRM) technique. Our method facilitates the physical understanding of the mechanisms leading to the far-field CD when a plasmonic excitation is involved.

2. Experimental Part

The samples were fabricated by using focused ion beam (FIB) on a 100 nm thick Au film evaporated onto a thin glass cover subtrate.In this structure ,scatterer,being a circular hole ,is clearly non chiral,however they have been arranged in a non--symmetric lattice. The lattice is defined by the primitive vectors \( a = a \cos \alpha \hat{x} + a \sin \alpha \hat{y} \) and \( b = b \hat{y} \) where a, b, and \( \alpha \) are the grating parameters as shown in the inset of the Fig. 1. We prepare several enantiomeric pairs of structure with varying period,for all of which the ratio between the primitive vector was \( b=1.1a \) and the angle \( \alpha =70^\circ \). When \( a\neq b \), then for arbitrary angle \( \alpha \neq 90^\circ \) the lattice does not have mirror symmetry.The periods varied from 430nm to 970nm in steps of 30nm.We used a laser at \( \lambda=785nm \) whose beam was expanded to properly fill the aperture of the illuminating objective (O1) through which the light was focused onto the sample. The back side of the sample (the glass substrate) was brought into contact with an oil immersion objective (O2) in order to collect the plasmonic leakage radiation. A tube lens, L1 (100 mm) was used to form an intermediate image of the plasmonic field distribution, while an additional Fourier lens (L2) imaged the k-space on the camera. Our LRM system allows one to observe even non-propagating scattering modes lying beyond \( NA=1 \) as well as the excited SP waves. By tuning the structure parameters, one can then manipulate the plasmonic excitation pattern. Due to the polarization state dependence of the scattering distribution the coupling to the SPs creates a polarization dependent absorption which inevitably leads to a general circular dichroism. By using our k-space CD spectroscopy we have revealed certain symmetry
properties and demonstrated the specific role of the plasmonic resonance in the far-field effective optical activity.

Figure 1: (a) k-space LRM setup scheme. The polarization state of the beam is chosen by a polarizer followed by a quarter-wave plate (QWP). The light is then focused with an objective O1 (NA = 0.4) on the sample. The imaging is done by means of an oil immersion objective O2 through the lens system (L1, L2) to generate a k-space image in the camera. (b) Scanning electron microscopy (SEM) image of structure with the period b = 970 nm. (c) A raw k-space image measurement. The red continuous line represents the SP momentum while the dashed lines are the circles of radius $k_{sp}$ centered at the neighboring diffraction orders centers, representing the secondary SP resonances due to the Floquet-Bloch theorem.

3. Conclusions

Finally, we show experimental study of the plasmon excitations in the optical activity of the structures with configurational chirality. By using our LRM technique in k-space we have demonstrated that(I) the scattering and diffraction orders have a polarization dependent intensity distribution and (II) the coupling to SP leads to a selective energy dissipation. These two effects lead to the overall optical activity and measurable CD spectrum. We believe that one of the key features of plasmonic-induced optical activity is the parity-odd correspondence between the k-space CD maps of the opposite enantiomer structures. We also studied the dependence of the CD on the structure periodicity from which a full dispersion property can be deduced. While the primary SP resonance is fixed with the respect to the incident wavelength, the secondary resonances stemming from the periodic boundary conditions may lead to significant variation of the resulting optical activity.

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References

Giant enhancement of chiral selective many-body correlation among emitters coupled with spirally stacked metal structures

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Abstract

We have studied the anomalously enhanced cooperative effect by metal structures sustaining the localized surface plasmons. In this contribution, we consider chiral spatial structures of the metal and emitter arrangements, and calculate the emission intensity of superfluorescence. The results show the remarkable difference by chirality in emission intensity, correlation between the emitters, and polarization distribution. We can expect that these results will lead to a new methodology in chiral research.

1. Introduction

High-density of quantum emitters in population-inversion state exhibit a cooperative emission (superfluorescence) through the correlated polarizations. Superfluorescence has three main characteristics [1]: the peak of the emission intensity proportional to the square of the number of the quantum emitters, the pulse width of the emission proportional to 1/N, and the coherence and the directivity in the emission. In recent years, the observation of superfluorescence in the ultraviolet region has been reported [2], and this phenomenon is expected to be applied as powerful coherent light sources for various regions of wavelength.

Conventional theories of superfluorescence consider all the emitters to exist within the same phase of the radiated light. On the other hand, we have recently developed a theory to analyze the emission time profile of arbitrarily-positioned emitters in arbitrary dielectric environment [3]. Based on this theory, we study the superfluorescence incorporating chirality into the environment. Chirality is the property that cannot be superimposed on their mirror images. In recent years, studies to enhance circular dichroism using metal structures, which sustain the localized surface plasmons, have been actively conducted. However, there has been no research on the role of chirality for the correlation effect among emitters. Considering the interaction between the helical emitters and spirally stacked metal structures, we can expect the strengthening of circular polarization characteristics of the fluorescent field, which leads to new light sources and sensing technologies for chiral molecules.

2. Theory

According to [3], the following Hamiltonian is used to calculate superfluorescence of the dispersed particle system,

\[ \hat{H} = \sum_i \hbar \omega_i \sigma_i \sigma_{i1} + \sum_{i,j} \int d\lambda \hbar \omega_k b_{\lambda k}^\dagger b_{\lambda k} \]

\[ - \int d\lambda \sum_i d_i \cdot \mathbf{E}(r), \]

where \( \sigma_{i1} \) mean the ladder operators of \( i \)-th emitter modeled as a two-level system, \( b_{\lambda k}^\dagger, b_{\lambda k} \) the creation and annihilation operators of the photon with the polarization direction \( \lambda \) and the wavenumber \( k \), respectively, \( \hbar \omega_i, \hbar \omega_k \) are the energies of the two-level system and photon, respectively, \( d_i \) is the dipole moment and \( \mathbf{E}(r) \) is the operator of the electric field. The intensity of superfluorescence is described by

\[ n_p(t) = \sum_{\lambda} \int d\lambda \frac{\partial}{\partial t} \langle b_{\lambda k}^\dagger b_{\lambda k} \rangle (t) \]

\[ = \frac{2}{\hbar \varepsilon_0} \sum_i \sum_{\lambda} \text{Im} \left[ d_i \cdot \mathbf{G}(r_i, r_i, \omega_i) \cdot d_i \langle \sigma_i \sigma_{i1} \rangle \right] \]

\[ + \frac{2}{\hbar \varepsilon_0} \sum_i \sum_{\lambda \neq \lambda} \text{Im} \left[ d_i \cdot \mathbf{G}(r_i, r_i, \omega_i) \cdot d_i \langle \sigma_i \sigma_{i1} \rangle \right], \]

where \( \mathbf{G} \) is the dyadic Green function. \( \mathbf{G} \) contains the spatial information of dielectric structures. In the present case, the dielectric structures surrounding emitters is described by the metallic susceptibility \( \chi_{\text{metal}}(r, \omega) \). Thus, \( \mathbf{G} \) can be numerically obtained from the Green function in a vacuum \( \mathbf{G}_0(r, r', \omega) \) by solving the following relation through the discrete dipole approximation (DDA) [4, 5],

\[ \mathbf{G}(r, r', \omega) = \mathbf{G}_0(r, r', \omega) \]

\[ + \int dr'' \mathbf{G}_0(r, r'', \omega) \chi_{\text{metal}}(r'', \omega) \mathbf{G}(r'', r', \omega). \]

3. Calculation model

Figure 1 shows a schematic diagram of calculation model. The metal structures are arranged so as to draw a left-handed...
helix and a right-handed helix around the Z axis. The light emitters are also arranged in the same way. (See, Fig. 1.) This calculation model has two characteristics. First, the model has 4 patterns depending on the combination of two chirality. Hereinafter, the combination in which the two rotation directions are aligned is called parallel, and the one in which they are not aligned is called anti-parallel. Second, the field enhancement effects by the metal are the same for all patterns. The enhancement effect by the metal depends on the distance between the metal and the emitters. In this model, we design so that the distance between respective emitters and their nearest metal structure are equal in all patterns. We also design so that total distance between all emitters and the metal structure is equal in all patterns. This ideal model can purely extract the relationship between the phenomenon of superfluorescence and the chiral characteristics of the system.

4. Result

If the chiral emitters are in a vacuum (without metal), the intensities of superfluorescence are the same between the left-handed structure and the right-handed structure of the emitters. Figure 2 shows the time profile of the emission intensity of chiral emitters surrounded by the chiral metal structures. The peaks of the emission intensity are different between the parallel and anti-parallel systems. The difference in emission intensity is 21.2% in the present model. Comparing this difference with the peak value of the intensity of chiral emitters in a vacuum, this difference is about 300 times larger than the peak value in a vacuum. We can expect to apply this large difference to sensing technologies for chiral substances. The difference in emission intensity between parallel and anti-parallel system also indicates that the intensity of superfluorescence shows the chiral selective light-emitting dynamics.

We also calculate the correlation between individual emitters and the polarization distribution in the local field on the emitters. In both calculations, a chiral selective difference appears. (Details of the results will be reported in the presentation.) In particular, the correlation between the emitter located near the edge of the metal structure and the others show a remarkable chiral selective difference from the correlation between the emitter located at the center of the structure and the others. The polarization distribution of the field near the edge of the metal structure also show a remarkable chiral selective difference from the polarization distribution at the center of the structure. Thus, as seen in the correlation and the polarization distributions, the magnitude of chiral-selective differences varies locally within the whole structure. Superfluorescence occurs by emitters that are correlated with one another through the spontaneously emitted field. As the growth of the correlation between emitters, the local chiral-selective differences propagate throughout the emitters. Thus, the local chiral-selective differences seen in the correlation and the polarization distributions create the large differences in emission intensity seen in Fig. 2 through the many-body correlation.

5. Conclusions

We study the superfluorescence of emitters with chiral structure surrounded by spirally stacked metal structures. The intensities of superfluorescence show that the difference by chirality is about 300 times larger than its peak intensity in a vacuum. These intensity profiles show that the two rotational directions (of emitters and metals) interact with each other, indicating the appearance of chiral selective light-emitting dynamics. We also clarify that correlation between emitters and polarization distribution show the local difference by chirality in the structures. This local chiral-selective difference creates the large difference in emission intensity through the many-body correlation. We hope that these results will lead to further investigations of many-body correlations in chiral system.

References

Theory of Single Molecular Near Field Circular Dichroism by Photo-induce Force Microscopy

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Abstract

We theoretically propose the near field circular dichroism (CD) of single molecules by photo-induced force microscopy (PiFM). Based on the extended discrete dipole approximation (e-DDA) incorporating the nonlocal optical response, we calculate PiFM CD map. The result indicates a greatly enhanced near field CD of single molecules.

1. Introduction

Photo-induced force microscopy (PiFM) is a technique to observe the near field optical response by measuring the laser-induced force arising between the sample and probe-tip of atomic force microscopy (AFM) systems [1, 2]. This force is strongly enhanced because of the localized near field by the plasmonic resonance that is sustained at the gap between the metallic substrate and metal-coated probe. (See, Fig. 1(a).) Recently, the scheme to eliminate the thermal effect on the photo-induced force has been developed [3, 4], which realizes the high-resolution PiFM and has achieved a resolution less than 1 nm. Further, we have theoretically proposed the unknown potential of PiFM [5, 6]. We can observe not only the morphology of the sample but also the spatial structures of the induced polarization that includes information of electronically excited states. By using the degrees of freedom of incident light such as frequency, polarization, and incident direction, we can obtain multi-directional information of electronic transitions including optical forbidden ones [6]. One of the fascinating aspects of near field observation is those related to the sample chirality. Recent reports of near field circular dichroism (CD) of metallic structures [7] and molecular CD near the metallic structures [8] have revealed quite different CD characteristics from those in the far-field observations.

In the present study, we have theoretically revealed the giant near field CD of a single molecule observed by PiFM. We calculate the PiFM map of the achiral and chiral molecules on the quartz substrate based on the extended discrete dipole approximation (e-DDA) incorporating the nonlocal response of molecules. The nonlocal optical susceptibility is calculated by the quantum chemistry calculation.

Figure 1: (a) Schematic diagram of the calculation model of PiFM system. (b) Enlarged figure of the part of (a) and cells for DDA calculation. (c) Molecules as the targets of PiFM measurement.

2. Model and Method

We model the probe-tip with a hemisphere of Au with 30 nm diameter. The molecule lies on the quartz substrate as depicted in Fig. 1(a, b). We assume a protrusion with 1 nm at the apex of the tip that forms pico-cavity [9], where the electric field is strongly localized and enhanced. The optical force exerted on the probe-tip is calculated according to the general formula [5],

$$\langle F \rangle = \frac{1}{2} \text{Re} \left[ \int_V \nabla E^*(r) \cdot P(r) \right], \quad (1)$$

where $E(r)$ and $P(r)$ are the total electric field and induce polarization at position $r$, and the integral is performed over the volume of the probe tip. $E(r)$ and $P(r)$ can be obtained by solving the following simultaneous equations,

$$\nabla \times \nabla \times E(r) - k^2 E(r) = 4\pi \kappa^2 \left\{ P(r) + P_{\text{mol}}(r) \right\}, \quad (2)$$

$$P(r) = \chi(r) E(r), \quad (3)$$

$$P_{\text{mol}}(r) = \int dr' \chi_{ij}(r, r') E(r'), \quad (4)$$

where $k$ is the wavenumber of light, $\chi(r)$ is the susceptibility of Au, $P_{\text{mol}}$ is the induced polarization of the molecule, $\chi_{ij}(r, r')$ is the nonlocal susceptibility of the
molecule. The integral is performed over the volume of the molecular wavefunctions. The molecular nonlocal susceptibility is calculated using the wavefunctions obtained with GAMESS US for the quantum chemistry calculation [10]. To solve the above simultaneous equations, we employ the extended discrete dipole approximation, where we use the multiple cell size, namely, we set the size of cells near the nano-gap region to be much smaller than those for the other region. As for the molecules, we consider phthalocyanine as an achiral molecule. Also, we consider azulenocyanine. (See Fig. 1(c)). If azulenocyanine molecule is lying on the substrate, the system including the substrate has chirality.

3. Results and Discussion

We calculated the force exerted on the probe-tip when the light is injected from the bottom as depicted in Fig. 1(a). Figs. 2(a, b) show PiFM map for phthalocyanine for the incidence of left and right circularly polarized lights. Also, Fig. 2(c) shows the $g$ value defined as $g_F \equiv 2(F_{\text{left}} - F_{\text{right}})/(F_{\text{left}} + F_{\text{right}})$, where $F_{\text{left(right)}}$ means the force for the incidence of left (right) circularly polarized lights. We can see that PiFM-CD locally appears. In the case of phthalocyanine, the average of CD over the displayed area vanishes. Figs. 3(a, b) show the PiFM map for the incidence of right and left circularly polarized lights and the PiFM-CD map for azulenocyanine. Also, in this case, clear PiFM-CD appears, and we should note that $g$ value becomes considerably large. Interestingly, the averaged value taken over the displayed area becomes finite for this molecule.

Thus, PiFM can reveal the chiral properties of samples in a striking manner even for single molecules. Similarly to the report in Ref.[7] for the metallic structures, the near field chirality appears even for an achiral molecule. However, the averaged value over the observed area vanishes, which can be understood from the symmetry of the molecule. On the other hand, near field CD and $g$ value of azulenocyanine are remarkably large. These results indicate that PiFM is a powerful tool to observe chiral characteristics of the near field around single molecules.

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References

The influence of the internal domain wall structure and chirality on spin wave dynamics in periodic magnetic stripe domain patterns

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Abstract

The study of the Dzyaloshinskii–Moriya interaction together with perpendicular magnetocrystalline anisotropy and film’s thickness influence on both the static magnetic configuration and the dynamics of spin waves in periodic aligned stripe domain patterns is provided. We analyze the sensitivity of excitation of resonant modes on polarization of the microwave field. Subsequently, we demonstrate in micromagnetic simulations the unidirectionality of spin-wave propagation along the domain walls and define the conditions for its occurrence.

1. Introduction

Magnonics is a subfield of magnetism concerned with the study of the dynamics of spin waves (SWs, or magnons that are coherent precessional perturbations of the magnetization) especially in the context of their utilization as an information carrier\cite{1}. The main advantages of SWs are microwave frequencies, their lengths which are 3-5 orders shorter than microwaves and at the same time SWs easily interact with other excitations in solids. Although until now mainly uniformly magnetized systems have been considered as media for SW propagation, recently non-uniform magnetic textures have been increasingly studied in this context\cite{2,3}. There are many advantages of using this type of system as an environment for SW propagation over uniformly magnetized nanostructured thin films. One of them is the utilization of domain walls as ultra-narrow waveguides that can be easily used to channel SW in different directions, even around a curved track what may be problematic in uniformly magnetized waveguides\cite{4}.

Magnetic textures characterized by spatial periodicity can be also used as magnonic crystals (an SW counterpart of photonic crystals) that do not require nanostructuralization. An example of them are aligned stripe domain patterns \cite{2,3}. Basic magnetic parameters determining the internal structure and chirality of domain walls are perpendicular magnetocrystalline anisotropy (PMA), film’s thickness, and Dzyaloshinskii–Moriya interaction (DMI)\cite{2,5}. These parameters together with exchange constant and saturation magnetization also determine the periodicity of such stripe domain pattern, which can be on the order of down to tens of nanometers.

2. Results and discussion

2.1. Dynamic magnetic susceptibility

Firstly, using micromagnetic simulations, we study how the spectrum of SWs depends together with the dynamic magnetic susceptibility \(\text{Im}(\chi(f))\) and static magnetic configuration in periodic magnetic textures on the value of both DMI and PMA. Fig. 1 shows the dependence of the dynamic magnetic susceptibility for magnetic thin films (saturation magnetization \(M_s=1420\ \text{kA/m}\), exchange constant \(A_{ex}=13\ \text{pJ/m}\), thickness \(d=2\ \text{nm}\) as a function of DMI constant \((D)\) and quality factor \((Q=2K_{PMA}/(\mu_0M_s^2))\), where \(K_{PMA}\) is the value of PMA) calculated for three different polarization of the microwave field used to excite SWs.

Figure 1: SW spectra in dependence (a) on \(D\) for \(Q=0.7\), (b) on \(Q\) for \(D=6\ \text{mJ/m}^2\), and (c) on \(D\) for \(Q=1.1\). The colors correspond to the intensities of the SWs excited by the microwave field of different linear polarization, i.e., the red color corresponds to microwave field polarized along the x-axis, the green to the polarization along the y-axis, and the blue color to polarization along the z-axis.

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Fig. 1). It can be seen that depending on the polarization of the microwave field, different modes are excited. For instance, applying a microwave field that is linearly polarized along the x-axis, only one resonant mode can be excited for the frequency range shown in Fig. 1. This is interesting property from application point of view, pointing at the selectivity of the SW excitation and also, the property suggesting topological property, the swap of the two bands order with no apparent interaction between them.

Figure 2: (a) Dispersion relation for SWs propagating along the axis of domain walls. (b) and (c) The amplitude of SWs in the middle cross-section of the film excited at the frequency (b) 3 GHz and (c) 7 GHz by the locally applied microwave field located in the region marked by the white-striped line. The modes corresponding to bands from (a) are indicated in regions of their localization in (b) and (c) by labels M0+, M0-, M1+, and M1-.

2.2. Unidirectionality of spin wave propagation along domain walls in aligned stripe domain patterns

Secondly, we study the propagation of SWs along the domain walls in aligned stripe domain patterns. In particular, we focus on modes for which nonreciprocity of propagation is present. In particular, we test in detail the unidirectionality of propagation along domain walls and the conditions for its occurrence. An example of the dispersion relation is shown in Fig. 2a, where we present the results obtained for 20 nm thick film characterized by $M_s=910$ kA/m, $Aex=1.45$ pJ/m, $D=0$, and $Q=0.6$. The results of micromagnetic simulations showing the propagation of SWs at two different frequencies are depicted in Fig. 2(b) and (c). Although the dispersion relation possesses a mirror symmetry, an effect of unidirectional propagation of SWs is clear, as the asymmetric intensity of the two bands. Namely, each mode is confined to the domain wall and prefers to propagate in every second domain wall, moreover it changes the channel with the change of the propagation direction. These properties are due to the fact that the neighboring domain walls have opposite chirality and the amplitude of mode $M1^+$ ($M0^-$) is greater in one type of domain wall whereas the amplitude of $M1^-$ ($M0^+$) mode is greater in the other type, as shown in Fig. 2(b) and (c).

3. Conclusions

In summary, we have investigated influence of the DMI and PMA on the magnetic configuration, and the spin-wave dynamics therein. In particular, the selectivity of the excitation of resonant modes by the microwave fields differing in the direction of linear polarization was demonstrated. We show also the possibility of excitation waves propagating in a given domain wall only in one direction. The conditions for the occurrence of this unidirectional nature are investigated and related to the chirality of the magnetization in the neighboring domain walls.

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References

High Harmonic Generation in Quantum Spin Liquids:
Analogy to Graphene, Semiconductors, and Superconductors

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Abstract
High harmonic generation (HHG) in matter has been extensively studied, and metallic systems have long been its central target among condensed matter. Recently, researchers have begun to extend the targets of HHG to other sorts of materials. We theoretically study HHG in magnetic insulators, especially, focusing on quantum spin liquids (QSLs). We show that HHG in QSLs may exhibit their characteristic features and the emergence of their even-order harmonics is controlled with a static external field in a class of magnets.

1. Introduction

Laser science and technology have been continuously developed and we can now use intense laser pulses in a broad frequency regime. High harmonic generation (HHG) is that when an intense laser with frequency $\Omega$ is applied to a material, electromagnetic waves with quantized frequencies $n\Omega$ ($n = 2, 3, 4, \ldots$) are simultaneously generated through the laser-matter interaction. HHG in conducting electrons in solids (such as semiconductors [1] and superconductors [2, 3]) have been actively studied, and much high-order harmonic generations (e.g., $n > 20$) can be observed due to the strong charge-light coupling. On the other hand, HHG in magnetic insulators have not yet been investigated well since the spin-light coupling is usually quite weak compared to the charge-light one. However, it means that there expanded a frontier in the study of nonlinear optical phenomena including HHG in magnets [4, 5, 6, 7]. In particular, the laser technology in terahertz (THz) regime [8, 9], whose photon energy is of the order of magnetic excitation energies, has been remarkably developed in the last decade. In fact, the second harmonic generation is observed, for instance, in an antiferromagnetic insulator [10]. Motivated by this background, we have theoretically studied HHG in quantum spin chains [11] and Kitaev honeycomb magnets [12]. These models can be exactly mapped to fermion models via Jordan-Wigner (JW) transformation, and as a result, we can make use of the analogy between conducting electron and quantum spin systems. With quantum master equation [14] including dissipation effect, we show that lower-order HHG can be observed in quantum magnets with currently-available intense THz laser [8, 9]. We also show that even-order HHG can be controlled by applying static magnetic or electric fields in a class of quantum spin chains [11] and Kitaev models [12, 13].

Below, we will shortly review our models, theory, and a few results, focusing on their essential aspects.

2. Models and Methods

We consider quantum spin chains and Kitaev honeycomb-lattice models [13] to study HHG in magnetic insulators. The Hamiltonians of a spin chain and the Kitaev model are respectively given by $H_{1d} = \sum_{j}(J + (-1)^{j}J_{d})(S_{j}^{x}S_{j+1}^{x} + S_{j}^{y}S_{j+1}^{y}) + (-1)^{j}H_{z}S_{j}^{z}$ and $H_{K} = -\sum_{\alpha=x,y,z} \sum_{\langle r,r'\rangle} J_{\alpha}S_{r}^{\alpha}S_{r'}^{\alpha} - \kappa \sum_{\langle r,r'\rangle} S_{r}^{z}S_{r'}^{z} - E_{dc}P$. In the spin chain of $H_{1d}$, $S_{r}^{z}$ is the spin-1/2 operator on $r$th site, $J$ and $J_{d}$ are respectively uniform and staggered exchange coupling constants, and $H_{z}$ denotes a staggered magnetic field (see Fig. 1 (a)). In the Kitaev model of $H_{K}$, $S_{r}^{x,y,z}$ is the spin-1/2 operator on $r$th site, $J_{\alpha}$ is the Ising interaction for the $\alpha$ bond $\langle r,r'\rangle$ (see Fig. 1 (c)). We focus on the isotropic case of $J_{x,y,z} = J$. The third-order perturbation for usual Zeeman coupling of a uniform magnetic field $\vec{H}_{z}$ generates a three-spin $\kappa$ term [13]. In the Kitaev model, a weak Zeeman coupling is irrelevant, but the Zeeman-coupling induced $\kappa$ term with $\kappa \sim |\vec{H}_{z}|^{2}/J^{2}$ changes the fermionic band structure.
as one sees soon later. In the final term \( -E_{dc}P \), we assume the existence of a magnetoelastic (ME) coupling: \( E_{dc} \) is an external dc electric field along the \( \hat{x} \) direction and \( P = -\eta_{\text{ME}}(\{S_j^x\}^2 - \{S_j^y\}^2) \) is the magnetostriction-type polarization with the ME coupling constant \( \eta_{\text{ME}} \). This type of ME couplings often appears in multiferroic magnets \([15]\).

These models can be mapped to fermion models via JW transformation. For example, in the spin channel, the JW mapping is given by \( S_j^3 = \frac{1}{2} \sum_i \langle \langle j| \hat{c}_i \hat{c}^\dagger_i \rangle \rangle \) and \( S_j^z = \frac{1}{2} - c_j^\dagger c_j \), where \( c_j^\dagger \) and \( c_j \) are respectively annihilation and creation operators of the introduced fermion. Figure 1 (b) and (d) respectively show the resulting fermion bands of the spin chain and the Kitaev model. In the spin chain, the inversion-asymmetric term \( J_{st} \) or \( H_{st} \) opens a band gap, and thereby the system can be viewed as a semiconductor with valence and conduction bands. In the isotropic \((J_{st}, \kappa, z = 0)\) pure Kitaev model with \( \kappa = 0 \) and \( E_{dc} = 0 \), we have a BCS-superconductor type Hamiltonian of the JW fermion, and the energy dispersion has gapless Dirac fermions around \( K \) and \( K' \) points like Graphene. However, a finite \( \kappa \) generates a mass gap of the Dirac fermions \([13]\).

As the spin-light coupling, we consider not only a usual ac Zeeman coupling \( H_{Z}(t) = -B(t) \sum_j S_j^3 \) but also an ac ME coupling \( H_{\text{ME}}(t) = -E(t)P \) \([15]\). The magnetostriction polarization is defined as \( P = \eta_{\text{ME}} \sum_j (-1/2)(S_j^+)(S_j^- + S_j^0) \) in the spin chain. Here, \( B(t) \) and \( E(t) \) are respectively magnetic and electric fields of the laser pulse, and these driven terms can also be fermionized in a bilinear form. The total Hamiltonian is therefore given by \( H_{\text{st}} + H_{1d} + H_{Z} + H_{\text{ME}} \).

These driven models can be decomposed into the sum of Hamiltonians \( H_{\text{st}}(k) \) with wave vector \( k \). Let us assume that dissipation effects in \( k \) subspaces are all independent of each other and the dissipative dynamics of each subspace is described by quantum master equation. In this condition, the density matrix of each subspace \( \rho_k(t) \) follows \( \dot{\rho}_k(t) = \frac{i}{\hbar}[H_k(t), \rho_k(t)] + \gamma_k \left( \rho_k(t) L_k - \frac{1}{2} \{ L_k^\dagger, L_k \} \rho_k(t) \right) \) \([14]\). Here, the first commutator in the r.h.s. describes laser-driven dynamics, while the second term \( (\propto \gamma) \) gives the dissipation dynamics and \( L_k \) is called the jump (Lindblad) operator. \( \gamma \) denotes the strength of coupling between the environment and the system and it is simply assumed to be independent of \( k \). We properly tuning the form of \( L_k \), making the system relax to its equilibrium state \([14]\).

## 3. HHG in Quantum Spin Liquids

The master equation enables us to compute the time dependence of any observable: We can calculate the magnetization \( m(t) = \frac{1}{N} \sum_j \langle S_j^z(t) \rangle \) and the electric polarization \( p(t) = \langle P(t) \rangle \). With their Fourier transformations, \( m(\omega) \) and \( p(\omega) \), the \( n \)th order spectra are given by \( I(n\omega) = |\langle n\omega \rangle|^2 m(n\omega)^2 + |\langle n\omega \rangle|^2 p(n\omega)^2 \). We numerically confirm that if applied THz laser pulse is strong enough within the currently available range (0.1-1 MV/cm), the lower-order waves with \( n = 2, 3, 4 \) can be detected. Here we will discuss two characteristics of HHG spectra \([11, 12]\).

The first is about the even-order spectra. If \( J_{st} \) is absent in \( H_{1d} + H_{\text{ME}}(t) \), the even-order HHG is shown to vanish from a perturbative approach. This is because the Hamiltonian with \( J_{st} = 0 \) is invariant under site-center inversion, while the polarization \( P \) is odd. We numerically verify that even-order spectra disappear for \( J_{st} = 0 \) while both even and odd-order harmonic peaks all appear for \( J_{st} \neq 0 \). This even-odd nature is reminiscent of HHG in semiconductors, in which the inversion symmetry breaking is necessary to create even-order harmonics. We also show that the even-order harmonics disappear for the driven Kitaev model \( H_K + H_{\text{ME}}(t) \) under zero dc field \( E_{dc} = 0 \).

The second is the continuous nature of the HHG spectra. We show that the HHG spectra are generally of continuous type as a function of \( \omega \). This is because \( H_{Z}(t) \) and \( H_{\text{ME}}(t) \) can be mapped to a particle-hole pair of JW fermions. This continuous spectra may be viewed as a clear signature of QSLs. If THz laser pulse is strong enough in \( H_K + H_{\text{ME}}(t) \), the continuous spectrum \( I(\omega) \) is shown to take a broad peak for \( \omega \) being close to the peak position of the fermion density of state (DoS). Namely, we can obtain the fermion DoS by measuring the HHG. Moreover, we numerically show that the peak of \( I(\omega) \) is proportional to \( k \) in a range of large \( k \). Since \( \kappa \) is proportional to cube of \( \tilde{H}_d \), the \( \kappa \) dependence of the peak is unique to the Kitaev QSL: In usual ordered magnets, the peak of \( I(\omega) \) comes from magnon excitations and the peak \( \omega \propto |\tilde{H}_d| \).

These results indicate that HHG in QSLs has high potential to show us their new information. We will report the more detail in the conference.

### References

Geometrical symmetry breaking in nanomagnets

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Abstract

Three-dimensional ferro- and antiferromagnetic nanoarchitectures possess a special interplay between their geometrical (topological) properties and the magnetic order parameter. The emergent chiral and anisotropic responses extend the intrinsic material properties and pave the way to novel functionalities of spintronic and spin-orbitronic devices.

1. Introduction

The conventional approaches to design magnetic devices at the nanoscale utilize planar technologies for extended films and straight racetracks for magnetic topological solitons. The progress in fabrication and characterization techniques allows to address complex-shaped planar and three-dimensional (3D) architectures [1–4]. In planar case, the boundaries of nanodots lead to formation of the highly inhomogeneous textures, such as vortices and antivortices. In 3D, the magnetostatics favours the spatially inhomogeneous shape anisotropy which is pronounced as a easy-axis anisotropy along wires or hard axis of anisotropy perpendicular to the film surface. These geometry-tracking interactions give a rise to the geometry-driven symmetry-breaking effects, such as topology-induced magnetization patterning [5], emergent anisotropic and chiral responses of Dzyaloshinskii–Moriya interaction (DMI) type [6–10].

2. Curvilinear ferromagnets

Shape anisotropy and coordinate-dependent anisotropy in strain-engineered samples force the magnetization in ferromagnets to be aligned with the geometry. The description of such samples in a local reference frame generated by the geometry allows to compare their responses with conventional planar ones. The competition of the anisotropy with the exchange interaction preferring the homogeneous magnetization leads to the development of the specific energy terms within the exchange energy, which are determined by curvature and torsion of nanowires [11], and principal curvatures in extended shells [12]. In this way, the geometrical symmetry breaking leads to the skyrmion pinning even in the intrinsically achiral materials [6,13]. In dynamics, there is a possibility to tune the domain wall [11] and spin wave dynamics [14] with respect to the applied spin-orbit torque and equilibrium texture.

3. Curvilinear antiferromagnets

While the field of curvilinear antiferromagnetism is in its infancy and mainly addresses spin chains, there are promising predictions of long-living highly inhomogeneous and geometrically frustrated states determined by the boundary conditions [15]. The effects of curvature stemming from exchange render antiferromagnetic spin chains arranged along space curves as chiral helimagnets [9] and lead to the emergent weak ferromagnetic response whose strength is determined by the curvature and torsion [10].

4. Outlook

The extension of spintronic and spin-orbitronic devices in 3D allows not only increase the density of functional elements in nanoelectronics, but also modify magnetochiral responses according to their shape. The sub-100 nm range accessible by the recent experimental techniques opens a way to the direct verification of theoretically predicted effects in curvilinear magnetism.

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References


Interaction of chiral light with topological singularities in plasmonic metasurfaces

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Abstract

Topological insulators (TIs) are electronic materials that have a bulk band gap but have protected (even in the presence of disorder) conducting states on their edge or surface. They provide unprecedented platform for quantum computation among other applications. During the past decade, the concepts of topological physics have been introduced into other fields, including photonic systems and efficient light confinement, guiding and localization have been achieved by using photonic crystal (PhC) optical systems with topological states. Furthermore, surface plasmon (SP) polaritons are 2D surface waves confining electromagnetic energy to subwavelength regions in the vicinity of a metal-dielectric interface. The SP's properties can be manipulated by causing them to interact with properly designed nanoscale metasurfaces and as these can by fabricated at great ease today, SPs play a vital role in nano-optics.

Here we present simple metasurfaces with different topologies supporting plasmonic edge states at the boundary between them. Preliminary experiments and numerical simulations show the achieved mode localization in line defects and point singularities. Line singularities are shown to support dark and bright modes. Point singularities show strong localization of light which can be further modified by the varying topological order of the structure.

Introduction

The field of topological photonics [1–4] has gained much interest lately in nanophotonics and optical communication communities [5, 6]. Topology [7, 8] has, in fact, been recognized as a novel degree of freedom in light-matter interactions as it provides an almost lossless medium for optical signals. Efficient light confinement, guiding and localization have been achieved by using photonic crystal [9] (PhC) optical systems with topological states [10]. These optical modes have emerged within the photonic band-gap [11] induced by the PhC periodicity at an interface between two or more regions with different topological phases [1, 12]. The optical edge states were shown to be topology protected and propagated with negligible scattering losses, in analogy with currents in so-called topological insulators that have been recently discovered [13, 14]. Modern nanofabrication techniques facilitate the realization of nanoscale periodic optical media with any desired geometry, which provides a practical advantage for the topology based nanophotonics with respect to a classical index-modulated systems [11, 15]. A special interest was focused on systems supporting surface plasmon (SP) [16, 17] modes - excitations of the bound electric charges in the vicinity of a metal-insulator interface. It has already been shown that these excitations are intrinsically topological in nature, and represent an edge state [18–20] of two adjacent media with an abrupt sign change of the dielectric constant.

Nevertheless, some further studies have discussed the possibility of further localizing the SP modes within a metasurface - the 2D equivalent of a metamaterial comprising a periodic structure with effective optical properties. Most commonly, such a system is realized via nanometric apertures or particles periodically arranged on a metal surface. Similarly to the aforementioned PhC, a specially designed doubly periodic metasurface can behave as a plasmonic crystal (PIC) with an accurately designed band-gap, where intentionally produced defects can localize and guide the SPs [21, 22]. Various configurations of PIC have been proposed for a variety of nanophotonics applications [23, 24]. It has been shown that such a mechanism provides a promising platform for future nanophotonic circuitry as well as various active plasmonic devices such as lasers and sensors [25–27]. It has also been demonstrated that exciting SPs by means of an anisotropic scatterer can lead to the geometric Berry phase that can further modify the propagation conditions of the surface waves [28–30]. The Berry phase has a topological origin as it stems from the light’s polarization manipulation defined by a path on a configurational space represented by the Poincare sphere [31, 32]. In this context, one may inquire whether the abrupt change of the Berry phase induced in the plasmonic metasurface may lead to the topological edge states.

In this talk we discuss the appearance of such plasmonic edge states at the boundary between two zones of a PIC with different topological phases. We propose to design a Bragg type plasmonic medium where no propagating SP modes are allowed. We suggest anisotropic rectangular apertures as the metasurface unit cell to be excited it by circularly polarized light. This configuration enables us to manipulate the topological phase of the excited modes that can be simply controlled by the aperture angular orientation. We experimentally investigate a number of
plasmonic metasurfaces comprised of two domains with an abrupt change in topology - a topological dislocation.

![Image](image_url)

**Figure 1.** Localization of plasmonic modes in topological dislocations. (a) Schematic of the localization principle based on the Poincare representation of the polarization modulation. (b) and (c) measured plasmonic modes along the dislocations.

1. Conclusions

We believe that our approach along with the experimental ability and the simplicity of the geometric design together with easy fabrication provide an important platform for the realization of topologically protected boundary plasmonic states. Such simple means of robust waveguiding and localization of light can play a vital role in the development of nano-photonic devices. In view of the scientific and practical interest of our findings we believe that further research in this field may pave the way to a novel nanophotonic circuitry based on topology.

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References

Phononics and acoustic metamaterials
Reminiscence of edge states in 1-dimensional hyperuniform acoustic materials

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Abstract

Hyperuniform materials are systems made from point distributions that suppress density fluctuations on large length scales. They present wide and isotropic bandgaps despite being highly disordered and degenerate. Here, we report the localization of acoustic waves at the interface between two 1-dimensional hyperuniform materials yielding in different states. Both materials represent an air-filled acoustic waveguide with rigid diaphragms acting as scatterers. Tunability of the band structure and emergence of the edge modes provide promising applications in wave control devices.

1. Introduction

Localized edge states arising at the connection of two materials being in different topological phases have long attracted attention due to their potential applications for robust transport of different types of electromagnetic waves. Recently brought into the field of acoustics, topological formalism has explained various phenomena occurring in mechanical systems [1]. Periodic acoustic structures have been shown to undergo a topological phase transition accompanied by an emergence of an edge localized mode by means of varying the geometry of the sample [2]. Since periodic structures are hyperuniform, suppressing scattering at all the wavelengths except the Bragg ones, a question arises about the possibility of realizing similar effects in disordered hyperuniform materials. Lately hyperuniform samples have appeared to possess wide and isotropic bandgaps in spite of being highly disordered and degenerate, allowing to observe localized gap states [3, 4].

In this work we obtain a hyperuniform sample by utilizing an optimization procedure, which minimizes the structure factor of a 1-D point scatterers distribution in the long wavelength regime. In the Born approximation it means the suppression of scattering in this region. We then construct a realistic structure consisting of an air-filled waveguide with rigid diaphragms placed at the calculated point scatterer positions. Changing its geometry we affect its bulk properties and investigate an interface mode localized at the connection of two waveguides in different phases. We perform a full wave numerical simulation using a Finite Element Method neglecting the viscothermal losses.

2. Results for the periodic structure

We start with a periodic case (see Fig. 1a)). If \( l_1 = l_2 \) this geometry can be related to the Su-Schrieffer-Heeger (SSH) model using the transfer matrix method. The junctions between the waveguide and the diaphragms stand for the particles in 1-dimensional chain and the spaces between the junctions stand for their coupling coefficients, which appear to be proportional to the spacing cross section. If \( l_1 \neq l_2 \) the system becomes more complicated though still replicates the features of the SSH model.

Two types of unit cells are possible – with the strong coupling inside the unit cell (Fig. 1b)) or between the unit cells (Fig. 1c)). The former configuration is in the topologically trivial state, while the later one is in the non-trivial state. The topological transition may be realized via interchanging the radii of the waveguide \( R \) and the diaphragms \( r \). The strong and weak coupling also interchange. The gap closing occurs when \( R = r \), i.e. a straight waveguide, and takes place at the first Bragg frequency \( f_b = c/(2(l_1 + l_2)) \). Then connecting these topologically different structures together should lead to the existence of an interface state.

Figure 2a) shows the dispersion diagram of two connected structures, exhibiting two gap states – for the connection via strong and weak coupling (wide and narrow spacing between two waveguides correspondingly). In both cases an interface localized state exists which has a symmetric shape for weak connection and anti-symmetric in the

\[ l_1 = l_2 \]
opposite case. The corresponding pressure profiles along the waveguide are shown in Fig. 2b) for anti-symmetric and in Fig. 2c) for symmetric modes. This behavior is similar to the results obtained for optical waveguides [5].

3. Results for the hyperuniform structure

We now implement the same procedure to the hyperuniform pattern as for a periodic one. After calculating the required diaphragms positions we construct a waveguide and connect it to its counterpart, where the radii $R$ and $r$ are interchanged. The dispersion relation shown in Fig. 3a) exhibits two gap modes for two types of connections similar to the periodic case. The behavior of the pressure profiles also resembles that of the periodic waveguides – there exist an antisymmetric-like (Fig. 3b)) and a symmetric-like (Fig. 3c)) modes. The gap modes are much more pronounced than in the periodic case and their amplitudes are comparable to the excitation field.

Though it is not straightforward to introduce a bulk topological invariant for a disordered structure with no center of symmetry, it exhibits reminiscences of topological behavior of a periodic waveguide. Since the hyperuniform structures are highly degenerate and disordered the observed localized modes are believed to be rather robust.

4. Conclusions

The results obtained so far illustrate an abundance of fundamental physical properties inherent to hyperuniform materials, such as correspondence with topological transition, feasible in highly ordered structures. Tunability of the band structure and robustness against disorder opens new possibilities for acoustic wave propagation control.

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References


Self-synchronization of Thermal phonons in a Charged Silicon Resonator System

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Abstract

Self-synchronization is an important collective behavior in many fields of physics and biology, in which oscillators are dynamic in a coherent state. In this work, through molecular dynamics simulations, we demonstrate that the Coulombic force coupled thermal phonons can be spontaneously synchronized, without any external driving. This synchronization is well understood by the study of frequency and phase synchronization degree. Moreover, we also found that the self-synchronization of thermal phonons significantly enhances thermal transport, by generating coherent thermal phonons around synchronization frequency. Our findings might promote physical understanding of the emergence of coherent phonons, and provide new perspectives in the engineering of nanoscale thermal transport.

1. Introduction

Synchronization of a population of coupled oscillators is a common phenomenon in nature, as observed in a wide range of physical and biological systems [1]. Through mutual interactions, oscillators can be self-organized in a collective motion, in which the synchronized units are locked to a unique frequency and phase. Because of the collective behaviors, the synchronization in optomechanics has attracted attention to achieve coherent operation in micromechanical systems [2]. Theoretical models are also proposed to understand the self-synchronization dynamics of oscillators, particularly the Kuramoto model, by which the origination of self-synchronization and its behaviors are well demonstrated [1].

On the other hand, coherent thermal phonons, collectively locked in frequency and phase, have been demonstrated as important thermal carriers in thermal dissipation and transport. As experimentally observed by Ravichandran et al. [3], the thermal conductivity of superlattice can be significantly enhanced by coherent phonons at low temperatures and short periods. Theoretically, Zhang et al. [4] also emphasized the significant effect of coherent thermal phonons on phonon-photon scattering mediated phonon decay. Thermal phonons are the thermally excited lattice vibrations, which behaviors similar to the one of mechanical oscillators. Naturally, the question of the efficient and controllable self-synchronization of thermal phonons can be raised. In this work, we study the self-synchronization of thermal phonons and explore its effect on thermal phonons generation and transport.

2. System and Simulation Setup

To directly investigate the dynamics of thermal phonons, we adopt the silicon pillared membrane as the platform. The pillars on the surface of the membrane act as the local resonators, in which phonons can be thermally excited. To make a frequency difference between the resonators, we consider two types of pillars with different height. Two systems are studied, with frequency difference $\delta \Omega_{1}=0.08$ THz and $\delta \Omega_{2}=0.12$ THz, respectively, with dimensions $1.09 \times 1.9 \times 2.2$ nm$^3$ and $1.09 \times 1.9 \times 2.7$ nm$^3$. Besides, to introduce a mean-field coupling between resonators, the long-range electrostatic force is considered by charging the top of pillars. The periodic boundary conditions are used in x-y membrane plane. We use classical molecular dynamic (MD) simulations to study the dynamics of thermal phonons. The covalent Si-Si interaction is modeled by the Tersoff potential [5]. The electrostatic interaction between electrons is modeled by the standard Coulombic formula with 25.0 Å cut off, and long-range interaction is simulated by the $pppm$ kspace method. All MD simulations are performed by using the LAMMPS package [6] with a timestep of 0.5 fs.

3. Results and Discussion

![Figure 1](image)

Figure 1. Self-synchronization of thermal phonons in frequency. (a) Synchronization degree in frequency ($r_s$) versus evolution time for two types of system, $\delta \Omega_1$ and $\delta \Omega_2$.
under different charging ratios. (b-e) Vibrational density of states (vDOS) of membrane, resonator-I and -II parts for the δΩ system with 0.2 % charging, respectively corresponds to the times at black circle in figure (a).

Firstly, the frequency information of resonators is obtained from the vibrational density of states (vDOS). As shown in Fig. 1(b), in the asynchronous state (uncharged system) the resonators have distinct resonance frequencies. The synchronization degree of frequency can be defined as $r_{p} = 1 - \Omega_{2}/(\Omega_{1} + \Omega_{2})/2$, thus $r_{p} = 1$ means the fully synchronized in frequency. However, in the charged system, the resonators become synchronized with the evolution time (See Fig. 1(a)). The peaks in vDOS of two resonators become degenerated after fully synchronized. Moreover, the frequency synchronization depends on the frequency difference and interaction strength between resonators. The small frequency difference with high charging ratio can be rapidly synchronized.

On the other hand, resonators are also synchronized in phase. The synchronization degree of phase reads as $r_{\Phi} = 1 - \left| \sum e^{i\Phi} / N \sum e^{i\Phi} \right|$, here $\Phi$ is the averaged phase and $\theta$ is the phase of resonators, and $N$ is the number of resonators in the system. The $e^{i\Phi}$ can be understood as the normalized displacement of individual resonators. As shown in Fig. 2(b), two neighbored resonators exhibit uncorrelated dynamics before synchronized, indicating $r_{\Phi} < 1.0$. As time evolution, the resonators are synchronizing and finally stationed to some degrees. Obviously, the synchronization degree of phase also depends on the frequency difference of resonators and the interaction strength from charging. Moreover, compared to the synchronization of the frequency the phase synchronization is much difficult to achieve, which agrees well with the Kuramoto model prediction.

![Figure 2. Self-synchronization of thermal phonons in phase. (a) Synchronization degree in phase ($r_{\Phi}$) versus evolution time for two types of system, $\delta\Omega_1$ and $\delta\Omega_2$ under different charging ratios. (b-d) Averaged displacement of two neighbored resonators versus evolution time for the system $\delta\Omega_1$ with 0.2 % charging, respectively corresponds to the times at black circle in figure (a).](image)

Furthermore, we also find that the synchronization of thermal phonons has a significant effect on thermal transport. As shown in Fig. 3(a), at the temperature of 100 K, the thermal conductivity of $\delta\Omega_1$ system can be enhanced by 210 % at 0.2 % charging, and 1210 % at 0.4 % charging. The enhancement is suppressed by increasing the frequency difference, in which the synchronization degree of thermal phonons is reduced. The calculated lifetime in Fig. 3(b) further evident the effect of synchronization on thermal transport.

![Figure 3. The effect of self-synchronization of thermal phonons on thermal transport. (a) Thermal conductivities versus temperature, for the asynchronous (uncharged) systems and synchronized (charged) with 0.2 % and 0.4 % charging. (b) Phonon lifetime versus frequency for the asynchronous system and the synchronized system with $\delta\Omega_1$ and 0.2 % charging.](image)

4. Conclusions

By using MD simulations, we observed the self-synchronization of thermal phonons in a charged silicon resonator system. Different from the other systems with external driving force or energy cost, thermal phonons are demonstrated to be spontaneously organized. The synchronization of thermal phonons is well demonstrated by the study of frequency and phase synchronization degree. Moreover, we also found that the self-synchronization of thermal phonons induces an unexpected and significant enhancement on thermal transport, by promoting the generation of coherent thermal phonons. Our findings provide a new perspective on the understanding of thermal phonons interactions and the study of coherent thermal transport.

Acknowledgements

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References

Diffraction-free propagation of Gaussian sound beam through layered water-steel structure

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Abstract

A finite-width acoustic beam propagating in a homogeneous medium spreads with distance. The spreading occurs due to the Fourier components which make nonzero angles with the direction of propagation. The rate of spreading is defined by the diffraction coefficient. We consider propagation of Gaussian sound beam through a periodic steel-water layered structure and demonstrate that for certain frequencies the diffraction coefficient vanishes. In the experiment the nonscattering propagation of sound was observed at distances about 1 m.

1. Introduction

Wave packet broadening is a result of dispersion, i.e. dependence of index of refraction on wavelength, n = n(λ). Spatiotemporally modulated optical pulses, so-called light bullets, may propagate without broadening [1]. A collimated beam with initial width σ0 conically spreads even in a non-dispersive medium. The angle of the cone Δθ ∼ λ/(σ0τ) in a homogeneous medium with linear dispersion. In an inhomogeneous medium this estimate is not true.

2. Beam evolution in dispersive medium

Consider a pressure beam at x = 0 of width σ0 along axis y, p(x = 0, y, t) = p0 exp (ik0y y - y^2/4σ0^2 - iω0t). The beam propagates in an anisotropic elastic medium with nonlinear dispersion ω = ω(kx, ky). The direction of the z-axis is chosen in such a way that the wave vector has two nonzero components, k0 = (k0x, k0y, 0). Independent evolution of each Fourier component of this beam leads to conical spreading

p(x, y, t) = p0e^{i(k0 - ω0)t} \frac{\exp \left( -\frac{(y + xV)^2}{4σ^2(x)} \left( 1 + \frac{Dx}{2σ_0^2} \right) \right)}{\sqrt{1 - \frac{Dx}{2σ_0^2}}}.

Here σ^2(x) = σ0^2 + (Dx/4σ0)^2, V(k0y) = ∂kx/∂kx|k=k0x, k0y| is the inclination parameter, and D(k0y) = ∂kx/∂kx|k=k0x, k0y| is the diffraction coefficient of the medium [2]. At long distances, x ∝ σ0^2/|D(k0y)| the width of the beam grows linearly with x and the beam approaches a conical shape with the opening angle Δθ = arctan(|D|). The diffraction is normal if D < 0, otherwise it is anomalous. Diffractionless propagation becomes possible if D(k0y) = 0, i.e. if the corresponding isofrequency surface has a flex point. This can be realized in solid-fluid layered structure.

3. Experimental results

Solid-fluid periodic layered medium supports propagation of sound with nonlinear dispersion. Exact dispersion relation is quite complicated since in the solid part sound wave has longitudinal and transverse polarization. In the long-wavelength limit, kd << 1, where k is Bloch vector and d is the period, periodic structure can be characterized by three effective parameters: the mass densities ρx and ρy and the bulk modulus B. Explicit formulas for these parameters can be obtained assuming that averaged acceleration and deformation of the unit cell is the same as those for homogeneous effective medium [3]. Dispersion relation for

![Figure 1: Band structure and the unit cell of periodic water-steel lattice.](image-url)
homogeneous anisotropic effective medium has the following form: \[ \omega^2/B = k_x^2/\rho_x + k_y^2/\rho_y. \]

Band structure calculated for the effective medium coincides well (in the long-wavelength limit) with the exact calculations, see Fig. 1. Careful study of the topology of the isofrequency surfaces shows that those corresponding to the second transmission band possess flex point. The experiment was performed at frequency \( f = 105.1 \text{ kHz} \) which lies sufficiently close to the \( \Gamma \)-point for the effective medium theory to be valid.

Numerical simulation in Fig. 2c clearly shows nonspreading propagation of Gaussian beam through steel-water lattice. Because of anomalous dispersion in the second transmission band the group and phase velocities have opposite directions, \( V_g \cdot V_{ph} < 0 \). Experimental setup is shown in Fig. 2a. Nonspreading propagation is observed for a lattice of 75 periods that correspond to a distance \( \sim 1 \text{ m} \). The width of the outgoing beam is only a bit wider than the incoming beam, Fig. 2b. Spreading for free water propagation is order of magnitude stronger, Fig. 2b. The effective parameters \( \rho_x, \rho_y, B \) are all negative at \( f = 105.1 \text{ kHz} \) and \( \rho_x/\rho_y \ll 1 \). Because of 1D periodicity negative refraction at the water-lattice boundary occurs for phase velocity. Group velocity suffers positive refraction, see Fig. 2c. Negative phase velocity refraction leads to backward wave propagation within the lattice.

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References
Giant extraordinary transmission of longitudinal acoustic waves

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Abstract

We demonstrate extraordinary longitudinal bulk-wave acoustic transmission inside a solid structure, acting as an acoustic meta-atom, that is connected between two tungsten blocks. By including concentric grooves of optimal dimensions, we show how the extraordinary acoustic transmission efficiency can be increased to a value exceeding 500, and how directed output beams inside solids can be produced. Applications include acoustic imaging and sensing.

1. Introduction

Acoustic metamaterials are non-naturally occurring structures designed to manipulate the propagation of sound. One phenomenon that has attracted attention in this field is extraordinary acoustic transmission (EAT), i.e. the passage of more acoustic energy than expected through a small sub-wavelength aperture. This has been extensively studied in liquid-solid or air-solid systems [1-2], on surfaces [3] and for shear bulk waves in solids [4], but only recently for longitudinal waves in solids [5]. Here we investigate longitudinal EAT in a solid structure at GHz frequencies by simulation. Such a structure, when repeated at sub-wavelength spacing, can form an acoustic metasurface.

Fig. 1 Simulation geometry for longitudinal bulk-wave transmission through a nanowire (all grooves shown)

2. Design and Simulation

The structure is shown in Fig. 1, consisting of two half-spaces of tungsten joined by a cylindrical nanowire surrounded by vacuum. Tungsten is chosen because of its effectively isotropic acoustic behaviour. To enhance EAT for incident plane longitudinal waves, we also make use of a concentric structure of circular grooves, as shown in Fig. 1, by analogy with similar geometries in fluid acoustics and optics. Simulations are conducted with PZFlex (Weidlinger Associates Inc.) in the time domain, and Fourier analysis is used to obtain frequency domain data.

We consider three cases, one in which there are no grooves, one in which there are grooves only on the input side, and one in which there are grooves on both the input and output sides, termed respectively the no-groove case, the input-groove case, and the input-output-groove case.

The radius of the nanowire is chosen to be a=2.5 nm and the length to be L=40 nm. Plane longitudinal bulk waves are impulsively excited on the input side, and travel towards the output side. In order to evaluate the extraordinary transmission of longitudinal acoustic waves, we make use of analysis regions for sampling the dilatation that are disc-shaped on the input side and dome-shaped on the output side. The volumes of these two regions are chosen to be the same [5]. We obtain values of the amplitude transmittance T(f) for longitudinal waves by making use of the average values of the amplitudes A_in and A_out in these regions at specific frequencies f. We then find, by analogy with the optical case, the EAT efficiency η(f) as follows:

\[ η(f) = T(f)^2 \frac{D^2}{d^2}, \]  

where D is the diameter of the disc analysis region and d=2a is the nanowire diameter. In our case D^2/d^2 = 19600. Here we ignore the effects of ultrasonic attenuation. Its effect is considered elsewhere [5].

3. Results

In the case of no grooves, EAT is expected to depend on the Fabry-Perot resonance of the pillar at frequency f_n:

\[ f_n = \frac{nv}{2L}, \]  

where n is the number of half-waves within the disc.
Here \( v_r \) is the wave velocity in the pillar, i.e. the extensional velocity of acoustic waves in a cylindrical rod, expected from literature values of density and elastic constants to be 4320 m/s for tungsten [6], and \( n \) is the mode number. The quantity \( L' = L + 2\Delta L \), where \( \Delta L \) is an end correction, which we find to be equal to 1.26a for our chosen aspect ratio. We obtain \( f_i = 46.5 \) GHz from the simulations, as predicted from Eq. (2) provided we use the above end correction. However, we only obtain a slight enhancement of the transmission efficiency at this resonance: \( \eta_f = 1.5 \). A detailed discussion of \( \Delta L \) is given in [5].

In the case of grooves of pitch \( p \) being present on the input side, it has been observed that resonances are introduced that depend on surface acoustic waves, in our case at a frequency [1]

\[
f_{G_m} \approx \frac{mv_r}{p},
\]

where \( v_r \) is the surface wave velocity, similar to the Rayleigh wave velocity 2470 m/s for tungsten. We choose 8 grooves with \( p = 40 \) nm, corresponding to \( f_{G_m} = f_i \). In contrast to the no-groove case, we obtain the giant transmission efficiency \( \eta_f = 500 \) at the first resonance, provided that we also optimize the groove depth (14 nm), width (6 nm) and position of the first groove (44 nm from the nanowire edge). Increasing the number of grooves to 14 produces a further increase in efficiency to 650 on resonance.

We also find that the installation of additional grooves at the output side, i.e. the input-output-groove case, leads to wave collimation at the output side [5], similar to that observed in fluid-solid systems and also in optics. The grooves act on the transmitted waves as sound radiators, and thereby modify the wave patterns in the far-field.

4. Conclusions

In conclusion we have considered the case of longitudinal bulk wave extraordinary acoustic transmission in a solid-to-solid system consisting of a cylindrical nanowire connecting two solid half spaces. We show that concentric grooves installed on the input surface can dramatically improve the transmission efficiency on resonance. Considerably enhanced values of transmission efficiency \( >500 \) can be obtained by tuning the first surface-wave resonance to the first Fabry-Perot longitudinal resonance of the nanowire. In addition, we find that the use of concentric grooves on the output side modifies the transmitted acoustic waves in the far field but not the transmission efficiency. We hope that in future this work will be verified in experiment, for example at lower frequencies for which ultrasonic attenuation can be neglected.

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References

On the use of a Helmholtz resonator to acoustically dope a Plate-type metamaterial

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Abstract

In this work, we analytically, numerically, and experimentally investigate the feasibility of an acoustic analogue of the photonic doping effect, i.e., the ability of changing the effective properties of a medium by embedding a dopant. We show that a one dimensional Plate-type Acoustic Metamaterial (PAM) can be efficiently doped using a single doping impurity, e.g., a tuned Helmholtz resonator. The influence of both the location of the dopant and the losses are studied.

1. Introduction

Since the advent of acoustic metamaterials, the search for extreme effective parameters, including zero-index media, has constantly led to the development of new structures and designs. On the one hand, zero-compressibility can be achieved using a 1D periodic structure of Helmholtz resonators [1]. On the other hand, zero density can result from a periodic arrangement of solid scatterers, membranes, or plates [2, 3, 4]. In the latter case, the Density Near Zero (DNZ) condition is due to the strong dispersion around the band gap associated with the resonance of the plate. This results in a stretching of the acoustic wavelength, a large phase velocity, and an almost constant phase distribution along the structure. In the case of a PAM, propagation without phase delay occurs in the negative density regime. The impedance matching condition is fulfilled at the plate resonance frequency leading to a full transmission but is accompanied by a phase delay related to the length of the metamaterial [5].

One way to force the system to present both zero-phase propagation and impedance matching, i.e., supersqueezing, at the same frequency is to compensate the impedance mismatch with a huge change in the cross-section at the air-PAM interface. Another way is to use a Density and Compressibility Near Zero medium (DCNZ), i.e., a medium in which both the density and the compressibility are zero, ρ ≈ 0, C ≈ 0, at a given frequency. One possibility to reach that condition is to consider an acoustic analogue of the photonic doping in electromagnetism. Liberal et al. [6] show that the inclusion of a single well-designed impurity can transform the effective properties of an Epsilon Near Zero (ENZ) medium into Epsilon-Mu Near zero (EMNZ), thus leading to full transmission without phase delay, regardless of the host geometry and location of the doping impurity.

In this work we investigate the feasibility of realizing an acoustic analogue of photonic doping in order to turn the DNZ behavior of a PAM into DCNZ. We propose to use a Helmholtz resonator as a dopant embedded in parallel within a 1D PAM. The effect of both the dopant localization and the losses is studied.

2. Lossless system

We consider a periodic arrangement of N = 20 thin elastic plastic shims (Young modulus E = 4.6 GPa, density ρ = 1400 kg.m⁻³, Poisson ratio ν = 0.4, thickness h = 102 µm) equally spaced by a distance Lgap = 1 cm and plugged into a circular waveguide of radius Rn = 15 mm, the properties of which have been widely studied [5]. Impedance matching, zero-density, and zero-phase propagation occur at three different frequencies, respectively \( f_m = 422 \text{ Hz}, f_{ϕ=0} = 414 \text{ Hz}, \) and \( f_{ϕ=0} = 405 \text{ Hz} \). A cylindrical Helmholtz resonator is used to shift both the zero-phase and the impedance matching frequencies at the zero density one. The length of the neck \( L_n = 20 \) mm of the Helmholtz resonator and the radii of the cavity \( R_c = 10 \) mm and of the neck \( R_n = 2 \) mm are fixed while the length of the cavity \( L_c \) is adjustable with a piston as it can be seen in Fig. 1(a). The Helmholtz resonator is tuned by varying \( L_c \) such that the effective bulk modulus of the total system tends to infinity at its zero density frequency. The inset of Fig. 1(d) shows that the condition is fulfilled for \( L_c = 32.06 \) mm, leading to a zero phase propagation with a full transmission and a zero reflection (b) at the zero density frequency (c) marked by the vertical dashed lines. As shown by Fig. 1(e-f), the presence of the dopant allows to have a constant pressure field along the metamaterial, leading to zero phase propagation and total transmission.

The influence of the location is discussed. As expected with the large stretching of the acoustic wavelength, wherever the doping element is embedded in the lossless PAM, doping occurs.
3. Effect of losses

The effect of losses on the acoustic doping of the PAM is investigated. As in most of the acoustic systems, viscothermal and viscoelastic losses have to be considered. The viscoelastic losses being predominant, the number of plates in the PAM is reduced to 6 plates. In doing so, the transmission of the PAM at the zero phase frequency \( f_{\phi=0} = 390 \) Hz is \( |T_{f_{\phi=0}}| = 0.47 \). A large frequency offset separates this zero phase frequency from the zero density and maximum transmission frequencies, \( f_{\rho=0} = 414 \) Hz and \( f_m = 439 \) Hz respectively.

As in the lossless case, the frequency offset between zero phase, maximum of transmission and zero density frequencies can be strongly reduced by embedding a well-designed dopant. As a result the zero phase propagation frequency \( f_{\phi=0} \) gets closer to \( f_m \). Nevertheless, the presence of losses prevents the perfect coincidence of maximal transmission and zero-phase propagation frequencies. It is worth noting that the quasi doping condition allows to have a non delayed propagation in the system with a 15% higher transmission, the measured (resp. analytical and numerical) magnitude of which goes from 0.42 (resp. 0.47) without dopant to 0.59 (resp. 0.53) in the doped configuration.

4. Conclusions

In conclusion, we demonstrated analytically, numerically, and experimentally the feasibility of acoustic doping using a plate-type metamaterials. We found that the doping phenomenon can lead to zero-phase propagation with high transmission, as soon as the amount of losses in the system is well controlled.

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Valley-protected Topological Lamb Waves in Asymmetric Pillared Metamaterials

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Abstract

We present a numerical study of the valley-protected topological propagation of zero-order antisymmetric (A\textsubscript{0}), symmetric (S\textsubscript{0}), and shear horizontal (SH\textsubscript{0}) Lamb waves at different domain walls between topologically distinct asymmetric double-sided pillared phononic crystals. The topological phase transition is obtained by imposing two large space inversion symmetry breaking perturbations on the height of some pillars in the unit cell. We demonstrate the unidirectional transport of A\textsubscript{0}, S\textsubscript{0}, and SH\textsubscript{0} modes at different domain walls in straight or Z-shaped wave guides.

1. Introduction

The discovery of the quantum Hall effect (QHE) at the beginning of the 80s, enabled the realization, twenty years later, of a new state of matter: the topological insulators. This new notion, that results from the study of charges transport in semiconductors, was soon applied to the spin current with the discovery of the quantum spin Hall effect (QSHE), before extended to other areas of physics, including acoustics and elasticity. Several types of topological phononic crystals have been proposed, exhibiting elastic energy transport properties, analogous to QHE or QSHE. To reproduce QSHE, an elastic metamaterial must include active components in order to break the time inversion symmetry. In elastic systems, this can be achieved with rotary gyroscopes and non-inertial platforms but at the cost of a great difficulty both in manufacturing and in assembly. QSHE emulation, which preserves the time inversion symmetry, only involves passive components, but it generally requires complex designs to obtain a doubly degenerate Dirac cone in the Brillouin zone [1].

Another strategy is to learn from the band structure of graphene which presents two valleys sufficiently distant from each other in the Brillouin zone so that there is no inter-valley diffusion. They then play the same role as the “up” and “down” spins in spintronic. Exploitation of this degree of freedom, which has proven to be another controllable degree of freedom for an electron in a two-dimensional honeycomb network, is called the quantum valley Hall effect (QVHE). It makes it possible to considerably reduce the geometrical complexity and the transition of topological phase can be simply carried out by breaking the space inversion symmetry in the unit cell. Consequently, a several configurations emulating QVHE [2] have been proposed to demonstrate theoretically and experimentally the unidirectional transport of elastic waves both in discrete models and in continuous structures. In the present work, we describe the realization of the topological valley-protected zero-order antisymmetric (A\textsubscript{0}), symmetric (S\textsubscript{0}), and shear-horizontal (SH\textsubscript{0}) Lamb waves at different domain walls between topologically distinct asymmetric double-sided pillared metamaterials. The Brillouin zone features a double-negative branch that gives rise to a degenerate Dirac cone upon folding. Different polarization-dependent propagation along the same primary direction along the constituent branches are presented. We further demonstrate the unidirectional transport of A\textsubscript{0}, S\textsubscript{0}, and SH\textsubscript{0} Lamb modes at different domain walls in straight or Z-shaped wave guides.

2. Results

2.1. Unperturbed structure

A schematic of the asymmetric double-sided metamaterial arranged in honeycomb lattice and the corresponding band structure are shown in Fig. 1(a) and 1(b) respectively. The unit cell features two pairs of pillars distant from each other by 230 µm, erected on a 100 µm thick plate. The diameter of the pillars denoted A (resp. B) in Fig. 1(a) is d\textsubscript{A}=120 µm (resp. d\textsubscript{B}=140 µm) and the height is h\textsubscript{A}=268 µm (resp. h\textsubscript{B}=160 µm). In addition, a thorough hole with diameter d=240 µm is drilled at each corner of the unit cell. These additional holes allow to soften the plate without noticeable alteration of the band structure. Both the plate and the pillars are made of steel whose Young’s modulus, Poisson’s ratio and mass density are E=200 GPa, v=0.3, and ρ=7850 kg m\textsuperscript{-3}. The dimensions of the structure were tuned for the resonances of the pillars to occur at a few MHz, a frequency range well suited for a forthcoming experimental validation of the numerical results. Two eigenmodes at 4.318 MHz create a degenerate Dirac cone at the corner K2 of the reduced Brillouin zone. At points H1 and H2, torsional motions around z-axis in pillars...
denoted BL and BR are predominant and therefore the lower pillars significantly contribute to the formation of the constituent branches of the degenerate Dirac cone.

2.2. Perturbed structure

Perturbation in the height $h$ of the lower pillars by $\Delta h$ allows to lift degeneracy of the Dirac cone. We have therefore considered the perturbed phononic crystal hereafter referred as PnPnC-I, derived from the unperturbed structure by setting $h_{BL}=h_{BR}+\Delta h$ and $h_{BR}=h_{BL}-\Delta h$. Instead of the degenerate Dirac cone, the band structure features now a complete band gap, centered around $4.314 \text{ MHz}$ if $\Delta h=+1 \mu m$. Setting $\Delta h=-1 \mu m$ leads obviously to a structure hereafter denoted PnPnC-II, having identical dispersion curves but which is absolutely distinct from the topological point of view.

We have investigated the propagation of the edge state in a straight and in a Z-shaped guide created by juxtaposition of PnPnC-I and PnPnC-II in the upper and lower domains respectively (see Fig. 2). Pillars having the height $h+\Delta h$ are then on both sides of the interface. An incident SH$_{0}$-polarized Lamb wave is launched from a point source at the interface between both domains the straight guide by applying $y$-axis polarized traction forces. Unidirectional propagation along the positive $x$-axis is observed in that case, in agreement with the positive group velocity at the valley $K_2'$. The waves are both positively and negatively refracted at the right edge of the structure. In contrast, A$_0$ mode, excited owing to out-of-plane traction forces, does not propagate and remains localized at the point source.

Inverting PnPnC-I and PnPnC-II domains amounts to modify the nature of the interface since pillars with small height are involved in that case. The opposite situation is then observed: SH$_0$ mode gets localized whereas A$_0$ mode propagates along negative $x$-axis.

In the case of the Z-shaped guide, quasi-unidirectional propagation of the $K_2'$ polarized SH$_0$ Lamb mode is achieved if the frequency is tuned to $4.314 \text{ MHz}$, whereas A$_0$ mode cannot propagate at this frequency. However, weak refracted waves appear at the left outlet, suggesting the occurrence of inter-valley scattering.

Finally, we have checked that the topological protection still occurs for larger values of $\Delta h$. Actually, the unidirectional propagation of SH$_0$ mode is not achieved anymore if $|\Delta h|=2 \mu m$, whether along the straight or the Z-shaped wave guides. This is attributed to a large inter-valley scattering in that case.

Figure 2. Amplitude of the out-of-plane displacement on the top surface under excitation of the $K_2'$-polarized SH$_0$ Lamb wave at $4.314 \text{ MHz}$.

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References


Asymmetric Elastic-wave Transmission in a Lossless Metasurface

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Abstract

Our research presents theoretical, numerical and experimental investigations of asymmetric elastic-wave transmission in a thin plate with a lossless elastic metasurface. A theoretical framework is developed to control the asymmetric elastic-wave transmission without tailoring losses. We numerically and experimentally demonstrate that the asymmetric wave behavior can be realized on basis of the higher order diffraction in a lossless structural waveguide. We further experimentally show that the novel phenomenon can be obtained within a relatively broad range of incident angles and frequency band.

1. Introduction

As a topic of particular recent interest, unidirectional or asymmetric transmission of acoustic/elastic wave has attracted much attention due to its tremendous potential for various practical applications. Asymmetric acoustic/elastic-wave transmission has been realized based on bulk metamaterials under the effect of nonlinearity [1], external energy [2], wave diffraction/refraction and surficial localized mode etc. However, the bulky volume of the manipulation structures, the limited incidence angles and narrow frequency bands still pose challenges for practical implementations.

On the other hand, as a kind of thin, 2D artificial sheet structure with subwavelength-scaled units and thickness, metasurface, can realize effective or more extraordinary wave manipulation in the form of lightweight and thin design, which has been demonstrated an ingenious way for both electromagnetic and acoustic wave control [3-7]. Recently, a pioneering work has been reported on the asymmetric acoustic transmission by utilizing a lossy acoustic metasurface [4]. On basis of loss-induced suppression of high order diffraction, asymmetric sound transmission has been theoretically and experimentally demonstrated in the gradient-index metasurface with tailored internal losses. Multiple reflections of high order acoustic waves were captured by the transient simulations. Inspired by this work, similar phenomenon of asymmetric acoustic transmission has been numerically and experimentally exhibited in another design of lossy metasurface composed of the coating unit cells [6]. It has been clearly shown in the above acoustic metasurfaces that loss factor plays a crucial role in the realization of asymmetric acoustic transmission. However, little research has been reported on the asymmetric acoustic transmission in lossless metasurfaces. In addition, compared to electromagnetic and acoustic waves, much less research has been devoted to the extension of metasurfaces to elastic waveguides since elastic waves in solid mediums exhibit more degrees of freedom and various wave modes. Even fewer attempt has been conducted regarding the asymmetric elastic-wave transmission in a lossless elastic metasurface.

Most recently, Fu et al. [7] have revealed that the transmission and reflection of higher order diffraction can be controlled by designing the integer parity of the acoustic metagrating. With the inspiration of this research, here we develop a theoretical framework, numerical and experimental realization of asymmetric transmission in a thin plate with a lossless elastic metasurface. We numerically and experimentally prove that the asymmetric elastic-wave transmission can be realized on basis of the higher order diffraction in a lossless structural waveguide. The delay induced by the multiple reflections of higher order diffraction is also experimentally captured. It is shown in both theoretical prediction and experimental measurement that the unique asymmetric transmission can be realized in the lossless elastic metasurface within a relatively broad range of incident angles and frequency band.

2. Results and Discussion

2.1. Numerical simulations

Figures 1(a) and 1(b) show the calculated out-of-plane displacement field contours in a thin steel plate with a lossless elastic metasurface for oblique incidences at +30° and -30°, respectively. The excitation frequency is 15 kHz. Asymmetric elastic-wave transmission along the two opposite directions are clearly observed. The transmitted wave for the positive incidence direction (+30°) has a dramatic reduction whereas the wave propagation in the negative direction (-30°) is almost totally transmitted. The
stark difference between the transmission properties under the two directions is exhibited.

Figure 1: Calculated displacement fields in a thin plate with a lossless elastic metasurface at (a) +30° and (b) -30° of incidence.

2.2. Experimental results

The elastic-wave propagation in the proposed lossless elastic metasurface are further experimentally captured. The measured displacement fields for oblique incidences at +60° and -60° are compared in Figures 2(a) and 2(b), respectively. The realization of asymmetric elastic-wave transmission by using a lossless metasurface is unambiguously verified.

Figure 2: Experimental displacement fields in a thin plate with a lossless elastic metasurface at (a) +60° and (b) -60° of incidence.

3. Conclusions

This study presents the theoretical, numerical and experimental verifications of asymmetric elastic-wave transmission through a lossless elastic metasurface. We numerically and experimentally demonstrate that the asymmetric wave behavior can be realized in a thin structural waveguide with a lossless metasurface design. This work could broaden routes to applications in elastic-wave control and directional transmission devices.

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References

Lightweight three-dimensional metamaterials for omnidirectional attenuation of mechanical waves and vibrations

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Abstract
Tailored composites with frequency band gaps are promising for mechanical wave control and vibration mitigation. Despite advances in their developments, the generation of omni-directional broadband band gaps remains challenging. We propose a class of lightweight phononic structures addressing this challenge. Omnidirectional performance is achieved by simultaneously activating several wave scattering mechanisms. Numerically estimated strong attenuation at ultrasound frequencies is validated in transmission experiments on polymeric 3D-printed samples.

1. Introduction
Phononic and acoustic metamaterials draw their ability to manipulate elastic waves from a delicately engineered architecture. Recent twenty years of intensive research have delivered numerous architectures for periodic metamaterials to activate bandgaps – frequencies of inhibited wave propagation – at various frequency regimes [1]. Yet, most of the proposed designs are essentially two-dimensional, i.e. suitable for attenuating only plane-polarized waves. Such configurations have limited, rather specific applicability, while many practical situations demand three-dimensional (3D) structures with omni-directional functionality. The development of 3D metamaterials with wide bandgaps is difficult due to wave multi-directionality, which results in a large number of modes to be suppressed, and intrinsically restricted band-gap width for each wave control mechanism [2, 3]. Besides, it is important to preserve light weight and compact sizes that further complicates the design problem.

Here, we propose two strategies to achieve omni-directional and wide bandgaps in 3D metamaterials based on simultaneous activation of several wave scattering mechanisms and validate these strategies experimentally.

2. Design and analysis
The first design strategy relies on the combination of pentamode lattices and phononic plates with 2D band gaps to produce 3D bandgaps.

Phononic plates with periodic cavities are ideal candidates to generate 2D bandgaps for in-plane waves. However, out-of-plane or oblique waves typically exhibit shear-type propagation modes at those frequencies, thus, closing the bandgaps [4]. Promising solution to suppress these modes can be found in the class of pentamode materials. A pentamode material consists of four tapered bars meeting at joints in a diamond-like lattice. Small radii of the spherical joints govern small values of the effective shear stiffness of the lattice that can be many orders of magnitude lesser than the effective bulk modulus. Hence, compressional and shear waves in such lattices are weakly coupled that results in the formation of broadband frequencies with isolated shear-type modes, i.e. bandgaps for compressional modes [5]. Interlayering phononic plates with pentamode lattices (Fig. 1) and adjusting their geometric parameters, one can tune the both bandgaps to the same frequencies. As there are no restriction on the plate pattern, the lattice can be combined with multiple designs of phononic plates [3] revealing universality of the proposed approach.

The second design strategy implies the activation of the three basic bandgap mechanisms, i.e. Bragg scattering, local resonance, and inertial amplification, to achieve wave attenuation in lightweight and compact structures at broadband frequencies. Specifically, a unit cell comprises bulky elements at the nodes of a cubic lattice, acting as masses, interchanged by smaller adjacent masses. The nodal and adjacent masses are connected by mirror-reflected sets of thin inclined ligaments (Fig. 2). The masses can have different shapes, and the number of the ligaments can be chosen according to requirements on the load-bearing capability of a metamaterial. The characteristic thickness and length of the ligaments govern the Bragg frequencies, the inclination angle controls the inertia amplification, and the mass-stiffness ratios are responsible for the local resonance bandgaps. By tuning the mentioned parameters, one can decouple transla-

Figure 1: 3D metamaterial for omnidirectional wave attenuation: (a) unit cell and (3) 3D-printed Nylon sample.
Figure 2: Metamaterial models with extremely wide omnidirectional bandgaps induced by simultaneous activation of three wave scattering mechanisms: (a-c) unit cells and (d-f) finite meta-structures made of 3x3x3 unit cells.

3. Numerical results
Dispersion and transmission characteristics of the developed designs are evaluated numerically (FEM) using Comsol Multiphysics 5.2 (see Ref. [4] for more details). For the phononic material in Fig. 1 made of Nylon ($E = 2$ GPa, $\nu = 0.41$, $\rho = 1200$ kg/m$^3$), the simulations reveal an omnidirectional bandgap of 32% width with the central frequency $f_c = 19.8$ kHz. For the metamaterials in Figs. 2a,d and Fig. 2b,e made of structural steel ($E = 200$ GPa, $\nu = 0.33$, and $\rho = 7850$ kg/m$^3$) and Nylon, the estimated bandgaps are of 55% and 131% with central frequencies $f_c^{(2)} = 3.68$ kHz and $f_c^{(3)} = 5.25$ kHz, respectively.

4. Experimental analysis
Several configurations were 3D-printed by means of SLS and MJF techniques from Nylon and tested experimentally. To measure the transmission of an elastic wave, we fix a sample between a piezo-actuator and piezo-sensor, which excite and measure the $x$-direction motion of the structure, respectively. A lock-in amplifier drives the piezo actuator and measures the structural response. The measured results are in good agreement with numerical predictions.

5. Conclusions
We proposed the design strategies for metamaterials with omnidirectional wide bandgaps by combining several wave scattering mechanisms. It paves the way for the development of various 3D phononic materials with target wave attenuation characteristics for multiple applications, especially with critical restrictions on structural weight and size.

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References
Observation of localized states induced by curved acoustic topological insulators

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Abstract

In this work, we design a two-dimensional curved acoustic topological insulator by perforating on a curved rigid plate. We experimentally demonstrate that a topological localized state stands erect in the bulk gap, and the corresponding pressure distributions are confined at the position with the maximal curvature. The robustness of the localized state is demonstrated by introducing defects near the localized position. The interaction between the geometrical curvature and topology provides a novel scheme for manipulating and trapping wave propagation.

1. Introduction

In the past several decades, topological insulators (TIs) have constituted an expanding research field in condensed matter, and the robust transport effect of boundary states against disorders has attracted intense interest in classical systems [1, 2]. Most recently, with the intensive investigations into TIs, higher-order TIs (HOTIs) with unconventional bulk–boundary correspondence has been proposed to support the lower-dimensional topological boundary states, thereby opening a new research direction in classical waves [3, 4]. Owing to the flexibility of the sample design in classical wave systems, two-dimensional (2D) HOTIs have been implemented extensively in photons, electrical circuits, and acoustic systems. Topological protected edge and corner states in 2D HOTIs can provide an avenue for designing novel functional components to increase the integration density and reduce the noise disturbance resulting from fabrication imperfections on integrated chips. In general, 2D TIs are designed on a flat surface; however, in most practical cases, curved topological structures are required. In this work, we designed a curved 2D second-order TI in an acoustic system by perforating the curved surface of a rigid wall based on the lattice distribution of the 2D SSH model. We experimentally observed that a topological edge state with the highest eigenfrequency is distinct from the edge states and exhibits strength mode localization induced by the geometric curvature. We also demonstrated that the topological localized state is robust against disturbances.

2. Experimental results

2.1. Design of curved topological insulator

Figure 1: Structural diagrams for a flat and b curved holey TIs. The eigenfrequency distributions for the flat and curved structures are depicted in c and d, respectively. The blue, red, and black dots represent the localized, edge, and bulk states, respectively.

Firstly, we investigated the influence of the geometrical curvature on the band structure of the 2D curved TI for the square lattices distributed on a curved surface. As a reference, we constructed a square crystal composed of a $6a \times 16a$ nontrivial region with $d/a = 0.75$ near a same-sized trivial region with $d/a = 0.25$ on the flat holey plate to form an interface, as illustrated in Fig. 1a. $d$ and $a$ are hole distance and lattice constant. Figure 1b presents the curved case, which had the same lattice distribution as the flat holey plate, with 480 holes located on the bump surface. Figures 1c and 1d depict the discrete eigenfrequencies for the flat and curved structures, respectively. It can be observed that there are 15 edge states supported by the interface presented in Fig. 1c, which are marked by red dots. For the curved case, as illustrated in Fig. 1d, the number of edge states was not changed, but the eigenfrequencies of the edge states were obviously increased. By determining the mode distributions of these eigenstates corresponding to the eigenfrequencies, an interesting phenomenon was observed whereby a localized state emerged at the top of the bump, as
shown in the inset of Fig. 1d. The eigenfrequency of this localized state is marked by a blue dot. The mode distributions of the topological edge states corresponding to the 12th edge states are depicted in the insets of Figs. 1c and 1d. The reason of localized state is that the bilaterally symmetrical geometrical shape led to bilaterally symmetrical distributions of the onsite energy of the holes on the curved surface; the eigenstate located at the top of the bump with the maximal onsite energy was isolated from the other degenerated edge states to form a topological localized state.

2.2. Observation of topological localized state

![Figure 2](image_url)

**Figure 2:** a) Schematic of experimental setup. b) Photograph of sample. The blue, red, and black stars represent the positions of the point source and the corresponding dots indicate the positions of the microphone. c) Measured pressure spectra for bulk, edge, and localized states. d) Measured pressure distribution of localized state with frequency \( f = 2661 \) Hz in all holes of convex surface. e) Schematic for introducing near and far defects into curved TI, indicated by cyan and orange circles. Transmission spectra for the structure including f near defects and g far defects obtained by simulation (blue dashed line) and experiment (red dashed lines). The black solid lines represent the results of the perfect structure as a reference.

We experimentally measured the topological localized state in a curved second-order TI. The holey structure was constructed via 3D printing of a curved epoxy resin plate and perforation on the curved plate surface. Epoxy resin can be treated as a rigid wall compared to air. Figure 2a presents the measurement setup. The sample was surrounded by absorbing sponges and a point source was placed at a distance of 3 cm from the curved surface of the sample. A microphone was placed at the back of the sample to detect the pressure amplitudes. Figure 2b indicates the placements of the source and microphone, marked by colored pentagrams and circles, respectively, for measuring the pressure amplitudes of the bulk, edge, and localized states. The transmission spectra of these eigenstates are depicted in Fig. 2c. It can be observed that the transmission peaks of the edge and localized states were clearly located in the bandgap of the bulk band. In particular, the frequency \( f = 2661 \) Hz of the topological localized state agreed very well with the simulation frequency \( f = 2660.7 \) Hz. It should be highlighted that the localized state was topologically protected because it was located in the bulk gap of the topological nontrivial structure. To observe the topological localized state in real space clearly, we also measured the pressure distributions of all holes on the curved surface at \( f = 2661 \) Hz in Fig. 2d. The result demonstrated the field confinement of the topological localized state at the structural top with the maximal curvature. We further introduced near and far defects into the curved structure by inserting solid cylinders into the holes, as indicated by the cyan and orange dashed circles in Fig. 2e. The bottom-right inset clearly shows the positions of the two types of defects. Figure 2f displays the transmission spectra of the topological localized state with and without the near defects. The black solid line is the transmission spectrum of the perfectly curved structure and the transmission peak was located at \( f = 2661 \) Hz. When introducing the near defects into the curved structure, the magnitude of the peak was impregnable and the topological localized state remained within the bandgap with negligible red-shifting, as indicated by the blue dashed line in the simulation and red dashed line in the experiment. Figure 2g presents a similar phenomenon for the introduction of the far defects.

3. Conclusions

We developed a 2D curved second-order TI by perforating a curved rigid surface, and demonstrated that the topological localized state can stand out from the topological edge states with an increasing geometrical curvature. Our experiments directly revealed the topological localized state at the top of the curved structure, and agreed very well with the simulation. Moreover, we demonstrated that the topological localized state is robust against defect disturbance.

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References

Localization of Surface Acoustic Waves in 2D Disordered Phononic Crystals Using Pump and Probe Spectroscopy

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Abstract

We report here some experimental results and reflections on localization. Some advancements have been made on the sample fabrication and the experimental set-up which allows us to study which allows us to study the dynamics of structure vibration related to the propagation of a surface wave in a disordered medium using pump and probe spectroscopy.

1. Introduction

The scattering processes of an acoustic wave (as well as electromagnetic and matter waves) by a scattering object have been well known for several years and are perfectly described by the diffusion theory. However, when the number of scatterers becomes important and their positions random, constructive interference effects come into play leading to a total halt of the scattering processes. The numerous works over the last decades showed that the slowing down of the diffusion processes can be fully characterized regarding the amount of disorder of the scatterers, as predicted by Anderson.

Besides the slowing down of the diffusion coefficient during the propagation of the acoustic wave, it is possible to highlight areas that are over vibrating related to the passage of the wave via time-resolved optical imaging techniques to demonstrate localization effects. Indeed, theory predicts that the transition from a diffuse to a localized state exists only in 3D, which means that in 2D all states are localized but are observable under certain conditions. It is possible to calculate the extinction distance of the diffusion coefficient which finally corresponds to the localization length of the wave and which obeys the relation $\xi = l \exp(\pi/2 k l)$, where $l$ is the scattering mean free path and $k$, the wavenumber; thus the spatial spread of the phenomenon is entirely driven by the parameter $k l$. Since all states are localized in 2D, it is necessary to have $\xi < L$, with $L$ the dimensions of the sample to have a direct measurement of this quantity, while taking care to have scattering mean free paths $l$ comparable to the wavelengths $\lambda$ that propagates in the sample.

2. Sample

The pump and probe spectroscopy method has been chosen for this study in the perspective of measuring co-localization phenomena of photons and phonons; but the first part of the project concerns the localization of surface acoustic waves. The idea of such an experiment is to measure the variations of reflectivity of a sample due to localization effects of a propagating wave which satisfies the condition $\lambda \sim 1$. As the method of generation of the acoustic wave uses a pulsed laser, the spectral content of such a wave is very wide band around 1 GHz, thus it is necessary to adapt the sample to satisfy the localization criterion $k l \sim 1$. For this purpose, a first sample has been fabricated in the clean room at INSP and consists of a SiO2 substrate on which a 70 nm aluminum layer is vaporized.

Figure 1: SEM image of the sample, the colored circles highlight the areas where the different wavelengths match the scattering mean free path related to the Gaussian distribution.

Then aluminum diffusers of diameter $\varphi = 300$ nm and height $h = 70$ nm are spatially distributed according to a
3. Results

The delay line allows us to study the propagation of the wave for about 8 ns after its generation. Plus, a 4f imaging system has been implemented on the experimental set-up, allowing to make scans on a 100 × 100 µm area offering the possibility to reconstitute a film of the wave propagation of the surface acoustic wave via the combination of the latter with the delay line. The Anderson localization being characterized by an out-of-plane overshoot caused by the passage of a wave that releases energy for the wavelengths satisfying the localization criterion, should be detectable with an interferometer. So using time-resolved pump and probe spectroscopy coupled to an imaging system, should make it possible to study the spatial and temporal dynamics of elastic wave localization phenomena in 2D. Un exemple de résultats typique obtenue à l’issue d’une mesure est illustrée en figure 2, et soulève un certain nombre de questions.

Figure 2 : 50 × 50 µm scan performed on the sample shown in figure 1, for a given time of the delay line. We can see the wave and the pillars represented as black dots.

4. Discussion

Although the localization criterion is satisfied for some areas of the sample, the dimensions of the pillars do not match the wavelengths of the modes propagating on the substrate surface. Further measurements have shown that typical wavelengths $\lambda \sim 5$-10 µm, which is one order of magnitude larger than the pillar dimensions: we are in the Rayleigh scattering regime. New samples with scatterers at wavelength dimensions are in preparation to determine which scattering regime would be most favorable. Moreover, the question of the quality factors of the pillars and the resonance frequencies have not yet been studied but should play an essential role in the localization phenomena.

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References

Fiber-integrated microcavities for efficient generation of coherent acoustic phonons

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Abstract
Coherent phonon generation by picosecond optical pump-probe spectroscopy is an important experimental tool for studying acoustic properties at the nanoscale. In this work, we integrate semiconductor micropillar cavities confining near-infrared light and 18 GHz acoustic phonons with single-mode fibers. This approach solves a major challenge of existing pump-probe experiments using mechanical delay lines: maintaining the spatiotemporal overlap of pump and probe beams on a micro-object to achieve well-controlled, reproducible mode matching conditions.

1. Introduction
Coherent phonon generation by optical pump-probe experiments [1] has enabled the study of acoustic properties at the nanoscale in planar heterostructures, plasmonic resonators, cells, micropillars, and nanowires. These experiments rely on the optical mode matching between the incident pump and probe laser fields and the optical modes of the structure under study. The efficient generation of coherent acoustic phonons relies on an efficient coupling of the pump field into the system, while the sensitive detection of phonons requires an efficient coupling of the probe to the optical mode undergoing a phonon-induced modulation. Since the implementation of these experiments usually requires a long mechanical delay line, the main practical challenges for its actual implementation are thus (1) stability of the optical mode overlap, (2) reproducibility of the excitation conditions, and (3) high power densities limiting the range of compatible samples. These shortcomings have so far been a roadblock in establishing the pump-probe as a quantitative spectroscopy tool for nanoacoustics.

2. Results
In this work, we simultaneously solve the three aforementioned challenges by integrating fibered systems into pump-probe experiments, lifting the necessity for any optical alignment during the experiments. We aligned and glued a single mode fiber onto an optophononic micropillar [3] beforehand as shown in Fig. 1.

Figure 1 (a) Optophononic micropillar cavity. (b) Device integrated into a single mode fiber. (c) Nanophononic response of the device measured by pump-probe spectroscopy. (d) Stability of the response over 42h. Figure adapted from Ref. [2].

Our approach allows us to observe stable coherent phonon signals over at least a full day and at extremely low excitation powers down to 1µW. This excellent stability enabled us to perform detailed power dependence studies revealing complex dynamics of the optical and phononic modes [4]. Considering these dynamics, we are able to optimize excitation conditions and observe a mutual coherence between the optical and acoustic mode. The monolithic sample structure is transportable and provides a means to perform reproducible plug-and-play experiments. The integration with fibers might also establish the missing link between high frequency acoustic phonon engineering and stimulated Brillouin scattering in structured optical fibers [5].

References
Spatiotemporal effective media for acoustic waves

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Abstract
Based on an approach of virtualized metamaterials with software-defined impulse response, we experimentally realize an acoustic spatiotemporal effective medium in dynamically switching between two resonating configurations with a modulation frequency at least 5 times higher than the signal frequency. We also establish the effective medium formula.

1. Introduction
To further extend the application of metamaterials, there are recent proposals and implementations to engineer their material properties to vary in time. These time-varying metamaterials enable the realizations of many exotic wave phenomena including magnet-free non-reciprocity [1], unidirectional frequency conversion and amplification [2,3] etc. On the other hand, when the modulation frequency is much faster than the signal frequency, the concept of temporal effective medium has been proposed as an analogy of the effective medium originally defined for the spatial domain [4]. In this work, we are interested to implement such a concept in terms of acoustic waves and to examine the effective medium formula in the temporal domain.

2. Spatiotemporal effective medium
Our experimental realization of spatiotemporal effective medium is based on an acoustic metamaterial of several virtualized atoms [5], as shown in Fig. 1(a). Each atom consists of a speaker $S_i$ and a microphone $D_i$ (with index $i$), which are interconnected by a small microcontroller. The microcontroller performs a time-varying convolution $S_i(t) = \int dt' Y_i(t, t')D_i(t-t')$. The time-varying convolution kernel $Y_i(t, t')$ is implemented by

$$Y_i(t, t') = a(t)g \sin(\omega_0 t' + \theta_i) \exp(-\gamma_i t') \Theta(t')$$

where $a(t)$ is a temporal modulation function, $g$, $\omega_0$, and $\gamma_i$ represent the resonating strength, resonating frequency, and resonance linewidth for a Lorentzian resonance respectively, $\theta_i$ is a line-shape tuning parameter, $\Theta$ is the Heaviside step function for representing causality. In this work, the amplitude modulation function $a(t)$ switches between two constant values, corresponding to two static configurations, labeled as A and B hereafter. The modulation, with a period defined as $\tau$, goes on as a square-wave modulation with duty cycle $\xi; 1 - \xi$. Each static configuration A or B, can exhibit a Lorentzian resonance in its static compressibility $\beta_A(B)(\omega)$ in frequency domain and therefore the modulation is alternating between these two resonating configurations, as shown in Fig. 1(b).

![Figure 1](image)

Figure 1: (a) A photograph of the acoustic metamaterial of three virtualized atoms in a 1D waveguide. (b) Schematic of the compressibility spectra for static metamaterials of configurations A or B, where the inset shows the amplitude modulation applied on the two static configurations. Here $T$ and $\xi$ represent the modulation period and duty cycle respectively.

For a particular convolution kernel set for the static configuration A, Fig. 2(a) shows the extracted compressibility $\beta_A$ (real and imaginary part) from experimentally measured scattering parameters of the metamaterials of the configuration. It is found that the experimental results (symbols) and the theoretical Lorentzian model resonating at around 1kHz (lines) match with each other well. Now, we modulate such a resonating compressibility spectrum by turning on and off the convolution kernel $Y$ alternatively in every $70\mu$s (equivalently $T = 140\mu$s) with duty cycle $\xi = 0.5$, $a = 1$ or 0 for the first half and second half of one modulation cycle). For such a time-varying metamaterial, we measured the scattering parameters and extracted the corresponding effective compressibility again with the same procedure. The experimental results (symbols) are shown in Fig. 2(b). On the other hand, from the temporal effective medium point-of-view, the constitutive parameter should be temporally averaged (with duty cycle $\xi; 1 - \xi$) by

$$\beta_{\text{eff}}(\omega) = \xi \beta_A(\omega) + (1 - \xi) \beta_B(\omega)$$

where $\beta_A$ for configuration A is the demonstrated compressibility in Fig. 2(a) and $\beta_B$ for configuration B...
corresponds to a value of 1, i.e. air without any scattering. The temporal effective medium regime is valid as the modulation frequency (1/T = 7.1kHz) is at least 5 times larger than the highest frequency (1.25kHz) in our interested frequency regime. The theoretical results in Eq. (2) is then plotted as the solid and dashed lines in Fig. 2(b), agreeing well with the experimentally extracted compressibility.

Figure 2: (a) The real and imaginary part of measured compressibility $\beta_A$ for a static acoustic metamaterial of configuration A are shown in black and red symbols respectively. Solid and dashed lines represent the real and imaginary part of theoretical Lorentzian model. Here the compressibility is normalized to the compressibility of air. (b) The experimentally extracted compressibility $\beta_{eff}$ for the temporal metamaterial. The solid lines show the model results according to the temporal effective medium formula Eq. 2.

3. Conclusions

We have experimentally realized the temporal acoustic metamaterials, and also established and verified the temporal effective medium formula. We will also discuss the spatiotemporal version by adopting different modulation phase delays among the different atoms. The extension to Willis coupling terms will also be discussed. We believe such a spatiotemporal metamaterial will provide a test-bed for future exploration of time-modulation-driven phenomena.

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References


Tuning the decay coefficient of sound in a 2D viscous metamaterial

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Abstract
The homogenization theory developed previously for a phononic crystal of cylinders embedded in a viscous fluid is used to calculate the decay coefficient of sound due to viscosity. We consider different Bravais lattices and different cross sections of the cylinders in order to tune the decay coefficient of sound. We observe that, in the low-frequency limit a phononic crystal with asymmetric unit cell behaves like a dissipative homogeneous metafluid with anisotropic viscosity.

1. Introduction
The pressure in a plane sound wave propagating in a viscous homogeneous fluid decays exponentially with distance according to, \( p(x) \sim e^{-\gamma_0 x} \). The decay coefficient \( \gamma_0 \) grows quadratically with frequency \( \omega_0 \), and depends on fluid density \( \rho \), two viscosity coefficients \( \eta \) and \( \xi \), and speed of sound \( c \) [1]. The decay length of sound (1/\( \gamma_0 \)) in water at frequency of 50 kHz is about 15 km, meaning that in water, dissipative losses can be ignored. However, dissipative losses are strongly increased if sound wave meets a solid object on its way. Oscillating fluid sticks to solid boundaries, forming a narrow viscous layer of thickness \( \delta \), where velocity gradients greatly exceed the gradients in a free fluid, leading to much higher viscous losses.

In a phononic crystal, the volume occupied by the viscous boundary layers formed around solid scatterers usually constitutes a small part of the volume of the whole sample. It, however, strongly reduces acoustic transmission. For example, if sound propagates through a 2D periodic lattice of cylindrical rods embedded in water, the decay length is reduced by two orders of magnitude. Here, we use the recent develop analytical approach, for exact calculation of the attenuation coefficient in a two-dimensional (2D) phononic crystal in the low-frequency limit [2], to tune the decay coefficient for different 2D Bravais lattices and different cross sections of the scatterers.

1.1. Dissipation of acoustic energy
Propagating sound waves generate vibrations of pressure \( p(r,t) = p(r) \exp(-i\omega t) \) and velocity \( v(r,t) = v(r) \exp(-i\omega t) \). Within the boundary layer \( \delta \), velocity in a viscous fluid decays exponentially from its value in the bulk to zero at the interface of a motionless hard scatterer. The acoustic power (per unit length of a cylinder) dissipated around a hard scatterer is given by the following contour integral [1]:

\[
\dot{Q} = \frac{1}{2\sqrt{2}} \left| \int_{\delta} v(r) \, dl \right|
\]

The integration runs over contour \( \delta \), which is the circumference of the scatterer. This equation is used for the calculation of the dissipated power within a unit cell of 2D phononic crystal, and is valid if the interface can be considered as flat within the lengths \( \approx \delta \), i.e., \( \delta < L_0 \) where \( L_0 \) is the length of the contour \( \delta \) that separates fluid from solid. This inequality, together with the condition of homogenization, \( k_\text{ac} \rho c < 1 \), defines the frequency interval where the proposed theory is valid.

The decay coefficient for a wave propagating in a homogeneous dissipative medium is given by the ratio,

\[
\gamma_\text{ac} = \frac{Q}{2c_{\text{eff}} E_c}
\]

For the case of a homogenized phononic crystal \( E_c \) is the acoustic energy within the unit cell given by,

\[
E_c = \frac{1}{2} \int_{\delta} \rho(r) |v(r)|^2 \, da
\]

1.2. Pressure and velocity distributions in the low-frequency limit
The pressure \( p(r) \) in a periodic system is represented by a Bloch wave,

\[
p(r) = p_0 e^{i k \cdot r} + \sum_{G \neq 0} p_G (G) e^{i (k \cdot G) r}
\]

and the velocity \( v(r) \) is obtained by \( v(r) = \nabla p(r)/i \omega \rho(r) \). All the details appear in [2], but the distribution of velocity is,

\[
v(r) = \frac{1}{\rho(r)} \left[ \frac{p_0 e^{i k \cdot r}}{c_{\text{eff}}(k)} + \sum_{G \neq 0} \frac{Q_G (G)}{E_c} e^{i G \cdot r} \right]
\]

Here \( c_{\text{eff}}(k) \) is the speed of low-frequency sound calculated in Ref. [2]. Once the distribution of velocity is known from Eqs. (5) and (4), the dissipated power Eq. (2), the acoustic energy within the unit cell Eq. (3) can be calculated. Then the decay coefficient, after simple but cumbersome

\[
\gamma_\text{ac} = \frac{Q}{2c_{\text{eff}} E_c}
\]
calculations, obtained from Eq. (2) lead to the following result:

$$\gamma_{ph} = \frac{L_0}{2\omega c_{eff}(k)} \sqrt{\frac{\eta}{2\rho}} \frac{M(k)}{N(k)}$$

(6)

The explicit forms of the factors $M(k)$ and $N(k)$ appears in Ref. [3]. These factors take into account the microstructure of the phononic crystal and the details of the formation of the boundary layer. It turns out that depending on geometry of the unit cell this numerical factor can be as big as $\sim 10^3$.

1.3. Decay coefficient for an anisotropic lattice

We apply the previous results for a phononic crystal with a rectangular lattice and square cross sections. The decay coefficient given by Eq. (6) is plotted in Fig. 1 for square cross section of the cylinders in viscous water background versus filling fraction, at frequency $\omega/2\pi = 50$kHz, which is well below the fundamental band gap. The parameters of the scatterers are selected to be $10^3$ of those of aluminum. It is known that phononic crystals with anisotropic unit cell behave like metafluids with anisotropic dynamic mass [4]. Viscosity, being a dynamical property also turns out to be anisotropic. Higher losses are obtained for sound wave propagating along the x-direction. This result seems counterintuitive since longer viscous boundary layer is formed for sound propagating along y-direction. However, the length of this layer is not the only factor. Local dissipation is defined by velocity gradients, which strongly enhanced near sharp corners. Another important factor is the effective speed of sound $c_{eff}$ that appears in the denominator of Eq. (1). The effective speed of sound appears in the insert of Fig. 1.

Dissipation always slows down propagation of sound. This can be seen in the insert to Fig. 1. For the directions of 45 and 90 degrees, the dissipation is low, however, dissipation is essentially increased for 0 degrees, which leads to noticeable reduction of the effective speed of sound.

2. Conclusions

By applying a recently developed microscopic theory of sound decay due to viscous losses in a phononic crystal with a rectangular lattice of solid cylinders with square cross sections embedded in viscous water, we calculated the decay coefficient of sound propagating in the low-frequency limit when phononic crystal behaves like a homogeneous fluid. This homogeneous fluid exhibits anisotropic viscous losses if the lattice is asymmetric. The level of anisotropy and decay coefficient grow fast with filling fraction. Formation of viscous boundary layers around solid cylinders leads to enhancement of viscous losses as compared to free water.

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References

Double negativity in bubble metamaterials

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Abstract

The subwavelength internal structure of locally resonant metamaterials enables their description by effective medium approaches. Because of the very low frequency character of their resonances, their effective properties are usually believed to rely on the individual features of the scatterers and on their concentration rather than on their spatial distribution. However, I will show that double negativity can be achieved in a metamaterial populated solely with monopolar subwavelength resonators, such as air bubbles in water, by playing on their spatial distribution. A disordered set of identical bubbles in water is known to exhibit a large gap above the individual monopolar resonance. In the gap frequency range, the effective compressibility is negative while the effective density remains positive. But by introducing pair-wise spatial correlations, multiple scattering within a pair of bubbles leads to the formation of a transparency window in the gap, which is associated with negative values of both compressibility and density. A second strategy consists in positioning bubbles on a diamond lattice, meaning two bubbles in the primitive cell. In this second case, the negative branch can also be regarded as a metamaterial equivalent of the optical branch observed in the phonon dispersion relations of diatomic crystals.
Experimental investigation of defect modes in tubular phononic crystals

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Abstract

In this contribution the use of defect modes in phononic crystals for sensing applications will be discussed on the basis of different practical realizations. As a specific example, experimental results of wave transmission through tubular phononic crystals will be compared for different materials and in the presence of different geometric defects to the ideal crystal, as well as to reference measurements through a corresponding hollow tube and solid cylinder. Numerical results from finite element models validate the experimental data and are used to illustrate band gap suppression and defect modes.

1. Introduction

Introducing defects into a phononic crystal or acoustic metamaterial yields additional functionality for practical applications. One promising area are phononic-fluidic sensors exploiting localized defect resonances inside a phononic band gap. This requires initial investigation and optimization of the band gap for different geometric configurations of a solid, elastic matrix, where very large band gaps have been demonstrated for finite three-dimensional lattices [1, 2]. Secondly, it is advantageous to design the geometric defects to yield resonances inside such band gaps for the solid-fluid material combinations of interest, in order to separate the defect resonance from other modes. The use as chemical and biochemical sensors for liquid analysis by filling the defect with a fluid of interest has been repeatedly demonstrated in the past decade [3, 4, 5, 6]. The defect resonance is then directly linked to physical properties such as speed of sound, density, viscosity, molar mass, molar volume, and (adiabatic) compressibility. Subsequently, these devices can be used to accurately measure the concentration of different constituents [7]. Two aspects differentiate the real behavior of a phononic crystal sensor to the ideal operation principle. For one, intrinsic losses in the materials and fluids of interest must be accounted for, as they strongly affect defect resonances. And two, a real sensor is a device of finite dimensions, limiting the extent of any periodic arrangement. These effects have been recently validated in numerical and corresponding experimental analysis, comparing lossless and lossy materials as well as semi-infinite and finite geometries for the application as concentration sensor and for determination of the speed of sound of these aqueous mixtures [8].

In addition to presenting different work on phononic-fluidic sensors at the symposium, here we discuss an experimental study supported by numerical analysis with a unique type of lattice, a tubular phononic crystal (TPC). We illustrate the appearance of a strong band gap for a finite cylindrical lattice in addition to the effect of geometric defects and different materials on practical transmission results. Tubular phononic crystals are a class of periodically structured elastic cylinders for wave propagation along the revolution axis. In light of the ubiquity of cylindrical pipes, vessels, and capillaries for the technical and biological transportation of fluids, we envision these devices as tubular phononic crystal sensors for in-line monitoring of liquids [9]. This work was done as part of the ongoing collaboration project Tubular Bell, with partners in Germany and France. Further experimental results and numerical investigations can be found in our recent related publications [10, 11].

2. Design and fabrication of defects in tubular phononic crystals

2.1. Defect design

Periodically adding additional geometric features along the length or circumference of a hollow cylinder is the key design feature of a tubular phononic crystal. These features are placed on the outer rim only, since we want the inner tube to be undisturbed for unperturbed fluid transport. The features can exhibit both translational and cyclic symmetry. In the most simple case, outer rings are added periodically along the axis. The rings can then act as distributed local resonators. Changing the geometry of one ring or removing it completely constitutes a defect in the regular arrangement. Figure 1 shows a CAD rendering of the different TPC and reference designs. To be suitable for the different fabrication techniques necessary for the different materials used in this study, the outer tube diameter and lattice constant is set to 8 mm, with an equal width and pitch of five ring resonators and an inner tube diameter of 6.4 mm. The outer diameter of the rings is 14.2 mm. The defect is placed in the middle at the third ring position, with an outer defect ring diameter of 17.6 mm or a missing ring. Outside the periodic arrangement we extended the tube on both sides by a length of two times the lattice constant. Consequently, the total length of all investigated samples amounts to 72 mm.
Solid reference:
Tube reference:
TPC ring:
TPC with defect ring:
TPC with missing ring:

Figure 1: Design of a tubular phononic crystal based on a periodic arrangement of ring resonators, with geometric defects and reference samples.

2.2. Materials and fabrication

The samples are fabricated in three different materials, two polymers and a metal. The polymer samples are 3D-printed using DLP microstereolithography (MAX X27 UV385, Asiga, Australia) using a tough and stiff polymer (FusionGRAY, Asiga, Australia) and a soft, flexible, and rubbery material (3DM Flex, 3DM-Shop, France). The metal samples are sourced from a 3D-printing supplier using selective laser melting of stainless steel 316L powder (Materialise, Belgium). The steel samples are post-processed with fine powder and glass bead blasting, while the polymer prints are rinsed and cleaned with isopropanol. With resin printing of the tough polymer the highest geometric accuracy and surface smoothness is achieved, however all samples conform to the design parameters within a deviation of a few percent. The exact material properties of 3D-printed plastic and steel are not known. For the tough acrylic plastic and stainless steel 316L the properties are close to values found in literature.

2.3. Numerical simulation

For validation purposes we built finite element models of the different TPC and reference designs in COMSOL Multiphysics 5.6 using the solid mechanics module. As boundary condition we applied a surface impedance matching the ultrasonic transducers used in experiments to the end faces of the tubes. A time-harmonic velocity perturbation was applied as excitation to one end, and the transmitted velocity was measured at the other end. The samples were meshed with a mesh size of over ten elements per wavelength for the highest frequencies of interest. A frequency domain perturbation study yielded the simulated frequency spectra, which we compare to our experimental data in the following section. A more in-depth numerical study of tubular phononic crystals with and without liquid is currently in preparation by the project partners [12].

3. Results and discussion

Two ultrasonic contact transducers ($V103$-RM and $V153$-RM, Olympus, Germany) connected to a high-precision lock-in amplifier (HF2LI, Zurich Instruments AG, Switzerland) are used to measure longitudinal and linearly polarized shear wave (polarized along one perpendicular Cartesian axis) transmission along the cylindrical axis through all samples (illustrated in Fig. 2). In the following, relative transmission of the received signal amplitude divided by the output signal amplitude is plotted over frequency. The transducers have a center frequency of 1 MHz and a $-3$ dB bandwidth of 100%, but can operate effectively upwards of about 20 kHz. The measurement range of interest is up to 100 kHz for the polymer samples and up to 250 kHz for steel, owing to its higher speed of sound. The output amplitude was set to 500 mV. Piezoelectric transduction and mechanical coupling efficiency result in an upper transmission limit of approximately $-20$ dB, or 100 mV/V. Coupling to steel samples reduces the maximum transmission to around 10 mV/V due to the smaller contact area of tubes in relation to the transducer size, while material losses in polymer samples lead to a maximum transmission below 1 mV/V. Regions of transmission minima correspond to band gaps. Repeating maxima correspond to standing waves along the complete tube length, which are suppressed in the TPCs.

3.1. Steel TPC

Figure 3 illustrates the transmission through a steel tubular phononic crystal in comparison to solid and tube reference. A strong and clear band gap appears around 100 kHz for both longitudinal and shear wave transmission, with both gaps overlapping. Band gap suppression relative to the solid reference reaches $-80$ dB or 0.1 mV/V in steel, while transmission outside the band gap is similar to tube and solid references with nearly no losses. The band gap center corresponds to longitudinal and shear wavelengths of approximately 60 mm ($c_l = 5740$ m/s) and 30 mm ($c_s = 3270$ m/s), respectively. The TPC with a periodicity of 8 mm operates therefore way below the frequency of Bragg type scattering, demonstrating the local resonator effect of the periodic rings.

Figure 2: Illustration of the measurement and simulation setup for longitudinal (left) and linearly polarized shear wave (right) transmission through tubular samples.
In Fig. 4 the measured longitudinal wave transmission (solid lines) of the ring TPC in steel is compared with the defect designs. Changing the geometry of the third ring results in the appearance of an additional dip prior to the first band gap at 60 kHz and a defect resonance mode within the main gap at 116 kHz. Removing a ring instead introduces a resonance mode at 121 kHz. The behavior is similar in the numerical simulations (dashed lines) with a very good agreement on the band gap and most transmission modes outside the gap, however the defect resonances are here split into two distinct modes. The small secondary gap at 170 kHz is also predicted at a slightly lower frequency in the simulation. The mismatch can be mostly attributed to fabrication tolerances. We indicated four different regions/modes A-D. The behavior of the steel TPC at these four modes is shown in Fig. 5. The band gap behavior is clearly evident for A and B, with different rings and vibration modes contributing the local resonance to absorb the transmitted wave energy. Defect modes C for a larger ring and D for a missing ring highlight the effect of defect engineering to achieve narrow-band transmission inside a band gap.

The transmission of linear shear waves through steel TPC is given in Fig. 6. While some features similar to longitudinal wave transmission can be found, the defect resonances of an enlarged or missing ring are much less pronounced or cannot be excited by this kind of motion at all. The primary band gap spans a considerably larger frequency range from 60 – 140 kHz.

3.2. Polymer TPC

In comparison, the tough polymer TPC also displays a strong band gap for longitudinal waves (solid lines), which is in very good agreement with the numerical results (dashed line) in Fig. 7. The band gap for shear waves (dotted lines) on the other hand does not coincide with it. Additionally, the higher material losses in the printed polymer strongly dampen the defect modes due to larger or missing ring. Nonetheless, the effect of defect engineering is similar to steel samples.
Figure 7: Longitudinal (solid lines) and shear wave transmission (dotted lines) through tough polymer TPC, with numerical data (dashed lines) in good agreement.

For the tough and flexible polymers the center frequency of the first longitudinal wave band gap is around 35 kHz and 27 kHz, respectively. This corresponds to a wavelength of approximately 50 – 70 mm (exact speed of sound is unknown for the 3D-printed polymers). Band gap suppression relative to the solid reference reaches around -70 dB in the polymer samples. However, transmission outside the band gap is also suppressed by -20 dB or more in the polymers. Curiously, the hollow polymer reference tubes also display a band gap for longitudinal waves. Figure 8 illustrates this behavior that mimics a phononic band gap. The tough, stiff polymer tube has a strong band gap between approximately 71 – 89 kHz and the soft, flexible polymer between 47 – 65 kHz. This corresponds to longitudinal wavelengths of about 29 mm, about 2/5 of the length of the tube. The steel tubes do not display this behavior.

As shown in Figure 9, the displacement plot from the numerical simulation shows the tough polymer TPC yielding a pattern similar to steel for the phononic band gap. The band gap behavior for the tube is related to a traveling radial mode with a shorter wavelength than the longitudinal wave. For the combination of radius, wall thickness, and length of the tube, it leads to destructive interference of the traveling radial shear wave at the frequencies indicated above. Exciting with a linearly polarized shear wave does not couple to this mode and does not lead to a similar band gap.

4. Conclusions

In this contribution, design and experimental results of defects in tubular phononic crystals are demonstrated for three different materials. The transmission through the tubular phononic crystals without and with defects is compared to reference solid cylinders and hollow tubes. A periodic arrangement of only five local ring resonators added to the exterior of a tube yields a well defined and strong phononic band gap in metal and polymer samples. Changing or removing one ring to introduce a defect results in strong defect resonances appearing in the band gap of steel samples, which illustrates the use for defect mode sensing applications. The material losses in polymer samples strongly suppress these resonances. A feature of hollow polymer tubes is also documented, with the appearance of a band gap for longitudinal wave transmission related to a traveling radial shear wave.

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References


Machine learning for metamaterials and metasurfaces
Nanostructured Materials for artificial neural computing

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We show that optical waves passing through a nanophotonic medium can perform artificial neural computing. Complex information, such as an image, is encoded in the wave front of input light. The medium continuously transforms the wave front to realize highly sophisticated computing tasks such as image recognition. At the output, optical energy is concentrated to well-defined locations, which for example can be interpreted as the identity of the object in the image. These computing media can be as small as tens of wavelengths in size and thus offer extremely high computing density. They exploit sub-wavelength linear and nonlinear scatterers to realize sophisticated input-output mapping far beyond traditional nanophotonic devices. To enable these complex neural computing, we draw inspiration from artificial neural network and use stochastic gradient decent to optimize nonlinear nanophotonic structures with structural gradient computed from adjoint state method.
Deep-Neural-Network Enabled Metasurface Designs

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Abstract

Metasurfaces are being widely investigated and adopted for their potential for integrating multiple functionalities into a single, flat optical device. A key challenge in this field is the non-intuitive design process that produces designs based on specific electromagnetic requirements. Meanwhile, deep neural network (DNN) has been proven to be an effective solution to non-intuitive design tasks. In this paper, we detail a novel approach to design metasurfaces using DNNs and demonstrate some devices achieved based on this approach.

1. Introduction

Recently, several DNN-based approaches have been proposed and investigated for the inverse design of meta-atoms/metasurfaces [1, 2]. Compared to traditional design approaches that largely rely on iterative numerical full-wave simulations, these DNN-based approaches provide a time-efficient and accurate solution for the forward performance characterization [3] and inverse design [1, 2] of different types of meta-devices. In this paper, we propose a novel meta-atom inverse design approach enabled by a combination of different network structures for the fast characterization of meta-atoms with complex shapes and inverse design of various meta-devices.

2. Meta-atom modeling network (PNN)

We firstly present a novel predicting neural network (PNN) for the modeling and characterization of 3D all-dielectric meta-atoms. To expand the design space and demonstrate the network’s generality, our approach takes into consideration almost all design spaces of a meta-atom, which includes the meta-atom’s two-dimensional (2D) geometrical pattern, material index, thickness and lattice size. Without loss of generality, the spectra of interest were set to be from 30 to 60 THz (5 μm to 10 μm in wavelength), while the other parameters are created randomly within the ranges (all lengths in microns): thickness in [0.5, 1], refractive index in [3.5, 5], lattice size in [2.5, 3].

After trained with sufficient data, the proposed network is able to generate accurate phase and amplitude predictions of meta-atoms with complex shapes across the proposed spectrum. After the training error is stabilized and the training is completed, we employed the well-trained PNN to evaluate some randomly-selected meta-atom structures to visualize its prediction accuracy (Figure 1). Only the real parts of the complex transmission coefficients are plotted for demonstration purpose, while imaginary parts, along with the amplitude and phase responses, can be derived accordingly. This highly accurate PNN is later used as a critic to evaluate the performance of meta-atoms generated by inverse design networks.

3. Meta-atom inverse design network (GAN)

DNNs can also be employed for the inverse design of meta-atoms. Here we present a novel approach for designing free-form all-dielectric meta-devices based on the conditional Wasserstein Generative Adversarial Networks (cWGAN). Within GANs, a generator network learns to map from a latent space to a specified data distribution, while a discriminator network tries to distinguish the candidates given by the generator (fake meta-atoms) from the real data (real meta-atoms from training data). Repeated comparisons between generated and real data continually improve the performance of both the generator and the discriminator until the generated data becomes indistinguishable from the real data. At that point, the performance of the generated fake meta-atom designs are as good as the real simulated meta-atoms, and the model is fully trained.

As a demonstration, we trained a conditional GAN which

Figure 1: PNN predicted transmission coefficients (real part) compared to accurate results. Blue curves represent the PNN predictions, red curves are full-wave simulation results. Parameters including refractive index, meta-atom thickness and lattice size are shown on top of each subplot. 2D cross sections of each meta-atom are included as insets.
can generate meta-atom designs based on specific amplitude and phase design targets at 50 THz (6 μm in wavelength). After 3,000 epochs of training with collected data, both the discriminator and generator losses were minimized and stabilized. Several randomly selected phase and amplitude combinations were chosen to test the trained network model. For each phase and amplitude combination, we employed the (GAN + PNN) combined network to consecutively generate 100 qualified designs to check the generation stability and efficiency of the proposed approach (Figure 2). Given specific amplitude and phase targets, numerous diverse and qualified meta-atom designs can be generated within a few seconds, indicating that the proposed design approach is highly efficient and robust.

Figure 2: Meta-atom designs generated using a fully-trained conditional cWGAN model. 100 meta-atom designs are generated using the well-trained meta-atom design network for different amplitude and phase combinations, which are (a) 0.5 + 45° and (b) 0.8 + 180°. Blue dots represent EM responses of generated designs (simulated with FEM tools), red dots represent the targeted amplitude and phase conditions. A 2D pattern of each design is shown on the right in each subplot. Red outlines in each polar plot indicate the qualified designs with a pre-defined minimum threshold of ±0.1 amplitude error and ±10° phase error. 100% pass rate has been achieved for both cases.

4. DNN-enabled metasurface design approach

With the fully-trained meta-atom generative network, we demonstrate its potential through generating a focusing lens working at 50 THz. The lens was designed with a focal length of 60 μm under y-polarized plane wave incidence. The lens has a 140 μm × 140 μm aperture size, containing 50 × 50 meta-atoms in total. The phase profile of the lens under y-polarized incidence was calculated and later used as phase inputs for the generative network. The amplitude profile is designated to be uniform to maximize the focusing efficiency. Full-wave simulation for the whole lens is carried out and displayed in Figure 3d, where a diffraction-limited focal spot can be observed.

Figure 3: A metasurface focusing lens designed with the proposed “GAN+PNN” approach. (a) Front view demonstration of the metasurface focusing lens. (b) Top view of the designed metasurface lens. Only a quarter of the metasurface lens was designed, with the whole pattern being generated from symmetry by mirroring this quarter along the x and y axes. Several meta-atoms were enlarged and plotted in (c) for a better view. (d) Full-wave simulated E-field in y-z plane under y-polarized incidence.

5. Conclusions

DNNs enabled the possibility of fast forward performance predictions and inverse design of meta-atoms/metasurfaces. We have presented how different neural network approaches can be employed to model meta-atoms and inversely design different meta-devices including lenses. The proposed network structure can be widely applied for designing meta-devices featuring complex geometries and multifunctional responses to realize unprecedented performance.

Acknowledgements

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Inverse design in nanophotonics using deep-learning

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Recent introduction of deep learning into nanophotonics has enabled efficient inverse design process [1]. Once the deep learning network is trained, it allows fast inverse design for multiple design tasks. In this talk, we show several inverse designing nanophotonic structures using deep learning [1-8]. We firstly discuss inverse design methods that increase the degree of freedom of design possibilities. These attempts include designing arbitrary shapes of nanophotonic structures, that are not limited to pre-defined structures [2], and designing both types of materials and structural parameters simultaneously [3]. In order to design arbitrary shapes of structures, cross-sectional design images are designed by generative model. Also, for simultaneous design of materials and structural parameters, we developed a novel objective function that combines regression and classification problems. After then, we also discuss optimizing nanophotonic structures using deep learning. We use reinforcement learning to optimize structure parameters. Using reinforcement learning, an agent learns parameter space of an environment through the exploration and exploitation of the reward. After learning, the agent can provide the optimized design parameters from its own experience. Several meta-devices including dielectric color filter [4], high efficiency hologram [5], and perfect absorber [6-8] are designed using this method.

Figure 1. Designing nanophotonic structures using deep learning. (a) Designing structural images that are not limited to pre-defined structures, (b) simultaneous inverse design of materials and structural parameters, (c-d) design optimization for color filter and perfect absorber.

Unidirectional non-Hermitian structures on demand by genetic optimization

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Abstract

We propose a general approach based on genetic optimization to achieve ‘on demand’ asymmetric light transport in non-Hermitian structures. The procedure allows designing the imaginary part of permittivity distribution from a given (arbitrary) real part of permittivity distribution for asymmetric reflection in a broad range of frequencies. We demonstrate a selective spectral unidirectional light reflection control, in such a way that it switches from left to right (or vice versa) with varying operating frequency.

1. Introduction

Transmission/reflection is symmetric with respect to the propagation direction in Hermitian potentials, as it follows from reciprocity and energy conservation principles. In recent years, attention has been paid on the notion of breaking the spatial symmetry in materials with complex permittivity profiles, i.e. in non-Hermitian potentials. Non-Hermitian potentials attracted significant attention due to counterintuitive features, such as unidirectional and omnidirectional invisibility, coherent perfect absorption, and directionality fields, among others [1-5]. While 2D configurations of non-Hermitian systems have been proposed [6,7], still the planar non-Hermitian structures consisting of a stack of gain/loss dielectric layers are of particular interest for their compatibility with available fabrication techniques. We here propose a systematic approach, using genetic algorithm, to design unidirectional periodic and non-periodic planar structures. We consider a simple 1D system divided in several spatial areas; with different real values of the permittivity to seed the algorithm [see Fig.1]. Thus, the genetic optimization provides the corresponding imaginary part of the complex permittivity leading to a unidirectional PT-symmetric like arrangement. The final goal aims at designing periodic and non-periodic non-Hermitian structures, from a given arbitrary permittivity profile, that hold asymmetric light propagation at different spatial frequencies, as depicted in Figs. 1(b-d).

Figure 1: (a) Schematic design of a planar PT-symmetric like periodic structure for asymmetric left/right reflection. (b-c) Asymmetric spectra holding unidirectional reflection at two frequencies, either in the same or opposite directions, in the above periodic non-Hermitian structure. (d) Non-periodic structure showing a broad-spectra unidirectional behavior.

2. Numerical Results

The performance of the system is quantified by user-defined target functions, in terms of the transmission and reflection coefficients, as obtained by the transfer matrix approach that provides guidelines for the genetic optimization. We may impose a target function being frequency dependent to cancel reflection at different frequencies for different propagation directions and symmetric transmission close to 100%. We first study a five-layer periodic structure with given (arbitrary) real permittivity values, and search for the corresponding imaginary parts of the complex permittivity

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of each layer that lead to unidirectional reflectionless propagation from the left [see Fig.2(a)]. The same initial real permittivity distribution may seed the algorithm with a different target function that switches to reflectionless propagation to the left/right, with varying the operating frequency [see Fig.2(b)]. The asymmetric light propagation is accounted by asymmetric coupling between wavevectors, deriving from the asymmetric spectral permittivity distribution. We observe that the optimized permittivity values in the complex plane forms a closed loop that allow for asymmetric reflection for the designed structure [see the insets on Fig.2].

![Figure 2: Scattering properties of the five-layer periodic system as obtained from genetic algorithm with different target functions, and same original real permittivity distribution seed. The upper/lower row holds asymmetric reflection for two frequency ranges in the same/opposite directions. (Left column) Transmission and reflection coefficients for right and left incidence. (Right column) asymmetric spectrum of the corresponding optimal complex permittivity distribution. The insets depict the complex permittivity of the five layers forming a closed loop.](image)

We also consider a non-periodic case; we assume a forty-five layer’s structure and design the appropriate gain-loss profile for a given initial gaussian permittivity distribution to obtain asymmetric left/right reflection [see Fig.3]. The optimized complex permittivity with genetic optimization confirms the unidirectional behavior, reflection is completely suppressed from the left side for all frequencies, as accounted by complex permittivity fulfilling Kramer-Kronig relations in space.

3. Conclusions

We propose a feasible approach based on genetic algorithm to design non-Hermitian photonic structures for on demand optical responses, in a broad frequency range. We show that the procedure allows engineering frequency dependent asymmetric light propagation in periodic and non-periodic structures with optimized complex permittivity distribution.

![Figure 3: Scattering properties of the designed non-periodic non-Hermitian structure. (i) initial real permittivity profile (ii) corresponding imaginary part of permittivity profile computed from genetic optimization. (iii) Transmission and reflection coefficients for asymmetric light propagation. (iv) Asymmetric spectrum of the optimized structure.](image)

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**References**


Ultra-flat optics design platform for a high-efficient wavefront engineering

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Abstract

In this work we propose a universal design platform for the development of high-efficient wavefront engineering structures. We demonstrate the efficiency of this approach by designing a series of common optical devices with an efficiency exceeding 99%.

1. Introduction

The production of lightweight, portable and wearable optical devices is presently hindered by the bulky, expensive and hard to manufacture nature of traditional optics\cite{1}, \cite{2}. Metasurfaces, two dimensional arrays of sub-wavelength spaced nanoscale structures, offer the possibility to replace conventional optics with highly integrated and versatile flat elements \cite{2}, \cite{3}.

In this work, we propose a flat optics design platform by employing concepts from evolutionary algorithms to deep learning with convolutional neural networks (CNN), and demonstrate a general design framework that can furnish an arbitrarily designed system response in the frequency domain. The structures can reach a thickness as low as 50nm.

The goal of this design approach is to define the material response (e.g., reflection, transmission, phase,...) by acting solely on the resonance network parameters, irrespective of the microscopic properties of the material.

2. Methods

To tackle this problem we developed a new formulation of Maxwell equations by using the theory of generalized functions \cite{4}, reducing the dynamics to an intuitive set of coupled mode equations that are fully exact and sufficiently simple to analyze light-matter interactions of any type. A remarkable result of this partitioning scheme is to exactly reduce the complex dynamics arising from Maxwell equations to the following simple set of coupled equations:

\[
\begin{cases}
\mathbf{a}(\omega) = \frac{\mathbf{K}}{i(\omega - \omega_0) + \mathbf{K}^\dagger \mathbf{s}_+}, \\
\mathbf{s}_- (\omega) = \tilde{C}(\omega) \cdot \left( \mathbf{s}_+ - \tilde{K}^\dagger \cdot \mathbf{a} \right).
\end{cases}
\]

Although controlling the system response of the resonance systems is theoretically possible from the analysis of Eq. (1), it presents difficult challenges. For example the phase space of variables $W$ and $\tilde{K}$ grows exponentially in size with the number of points we fixed in the output response of the material.

We overcome these issues by developing an Autonomous Learning Framework for Rule-based Evolutionary Design (ALFRED). ALFRED consists of two main parts: an optimizer and a predictor. The global search for the best configuration of resonances is carried out by a particle swarm optimizer (PSO), which is very effective in high-dimensional global optimizations \cite{5}. The swarm performs a collective search based on an ensemble of randomly defined tentative particles solution (Fig. 1a, bee), with each particle representing a specific geometry of boxes resonators that can solve the problem. The main bottleneck to this optimizer is the time required for each particle to evaluate the value of the cost function. In this computation, each particle needs to calculate the output response from the structure by using first principle simulations carried out by finite difference time domain (FDTD) codes.

In our problem, we usually optimize tens of different degrees of freedom and the resulting FDTD time is around hundreds of thousands core hours for a single structure. For this reason, we developed a neural network predictor unit attached to each particle (Fig. 1 a), which predicts the outcome of FDTD simulations. Predictor network takes an array of a single unit as an input and maps it to a transmission/reflection/phase spectra. This network consists of a two main parts: encoder, presented by convolutional neural network (CNN), which transforms an input image space to a low-dimensional feature representation, and a decoder, a group of fully-connected networks (FCN) connected to a feature space through a non-trainable optical switch, mapping a feature space to spectral points.

3. Results

Figure 1c-f show one of the structures obtained by ALFRED for a broadband polarizing beam splitter. The cost function $F$ (Fig. 1c) minimized is defined as follows:

\[
F = \left| 1 - s^{TE}_{\text{\scriptsize out}}(\omega_0) \right| + \left| 1 - s^{TM}_{\text{\scriptsize out}}(\omega_0) \right| + \left| \frac{ds^{TE}_{\text{\scriptsize out}}(\omega_0)}{d\omega} \right| + \left| \frac{ds^{TM}_{\text{\scriptsize out}}(\omega_0)}{d\omega} \right|
\]

with $s^{TE}_{\text{\scriptsize out}}(\omega_0)$ and $s^{TM}_{\text{\scriptsize out}}(\omega_0)$ being the transmission and reflection measured on a flat scattering wavefront at the operating frequency $\omega_0 = 2\pi c/\lambda_0$ for TE and TM polarizations,
respectively, and $\| \cdot \|$ the norm. The cost function $F$ maximizes the transmission for TE and the reflection for TM on a flat wavefront and provides broadband performances by minimizing the first derivative in transmission and reflection.

The proposed framework is fundamental in our recent experimental paper [6] in which we presented a plethora of high efficient devices, including, but not limited to: polarizing beam splitters, dichroic mirrors and metasurfaces for a novel 2-pixel display technology.

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References


![Figure 1: Optimizer (a) and predictor (b) units of ALFRED. Search process (d) for an optimal structure (e) with desired response (c). Output (f) from FDTD simulations for the obtained polarizing beam splitter.](image-url)
Integrated All Optical Passive Neural Network Using Silicon Metalines

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Abstract

We propose a fully optical architecture for implementing deep neural network using nano-photonic integrated circuits. Fully optical matrix multiplications are performed using silicon based metalines. The proposed whole-passive optical neural network is very compact and works at the speed of light, with less energy consumption than state of the art electronic counterparts. Various complex functions that is performed by digital neural networks can be implemented by our proposal at the wavelength of 1.55µm.

1. Introduction

Optical neural networks (ONNs) have been suggested as a high-speed, low-power and ultra-broad bandwidth alternative to digitally implemented neural networks. Also, the parallelism of optics motivates implementing neural networks using light. Recently optical neural networks are realized by using diffractive layers with locally modulated thickness [1], metamaterials with deep subwavelength distribution of discrete phase shifts [2], multi-layer aligned metasurfaces [3], etc.

Metasurfaces are arrays of subwavelength structures capable of shaping the wave-front (phase) of incident electromagnetic waves. In [4], an ultra-short, low-loss and broadband mode size convertors and metasystems performing Fourier transform and spatial differentiation based on on-chip 1D high-contrast transmit array (HCTA) is demonstrated. Here, using similar HCTAs, we propose an optical neural network design enabling efficient processing and analysis of data in parallel, directly on chip. To test the practical performance of our design, the network is trained as a digit classifier to classify handwritten digits from zero to nine.

2. The proposed design

The optical architecture consists of 1D rectangular etched slot arrays as “metalines [5]” in the silicon-on-insulator (SOI) platform. We fix the lattice constant (a) of the metalines to be approximately one third of wavelength (500nm) and the width of slots (ω) to 140nm. The length of the slots (L) can be adjusted to enable free control of the propagation phase within the full 0-to-2π range [4]. It is assumed that the transmission loss is negligible for all the meta-atoms, and the output wave of each meta-atom is determined by the propagation phase shift of its input wave. As shown in Fig. 1, the optical neural network consists of five metalines, each with 98µm length, which are precisely aligned with 21.7µm separations. After light exits the final (fifth) metaline, it propagates 21µm, until it reaches the output line of the network with ten detector regions, arranged in a linear configuration. A specific digit is assigned to each detector.

Figure 1: The schematic of the proposed optical neural network, the size of which is 64λ by 80λ, while λ is 1.55µm.

To demonstrate the intelligence of our ONN to perform desired tasks, we train our network as a digit classifier, where 10 handwritten digits, from 0 to 9 are chosen for recognition. The training is accomplished by computer to advance the design. Once the design is finalized, the inference/prediction is fully optical. Training is performed using 20,000 handwritten images from MNIST handwritten digit database. Each pixelated image consisting of 14×14 pixels, is converted to a vector and then encoded as the intensity of input light. The lengths of the slots in meta-atoms are chosen as the learnable parameters during training process. The optimization problem involves 980 design variables (196 meta-atoms per metaline, and five metalines). For a specific digit, when the output signal is accurately distributed such that the total intensity incident upon the expected detector corresponding to that digit has the greatest value comparing to the other detectors, the classification can be considered successful.

Following the mathematical framework presented in [3], the phase of meta-atoms (and correspondingly the length of the
slots) are adjusted in the search of minimum cost function corresponding to squared errors between the desired set of output intensity distributions, and realized set of intensity distributions at a training iteration. The cost function is iteratively minimized using the method of mini-batch gradient descent. Each batch consists of 200 different input images. To compute the gradient with respect to all of the optimization parameters, an adjoint gradient method is used [3]. The cost function can be calculated through a forward propagation model. In this model, each meta-atom on a single layer introduce a phase modulation on the input electric field at that meta-atom. The produced electric field at the output of the corresponding metaline is decomposed into a superposition of plane-waves using the discretized Fourier transform [3]. Each plane-wave is multiplied by an appropriate phase factor accounting for the phase accumulated as the wave propagates to the next layer. An inverse Fourier transform operation is performed to determine the resulting electric field at the input of the next metaline layer [3]. This propagation model helps multi-layered metaline systems to be simulated efficiently. Fig. 2 shows the cost values for the training set and the accuracy values for the test set for each Epoch during training procedure. After 100 Epochs the accuracy is over 89% for the training set.

figure 2: The cost value (blue line) on training batches and accuracy (red line) on test set of the proposed ONN during training process at each Epoch.

Once the training is done and an optimized design is achieved, the design is tested using 10,000 handwritten digits contained in MNIST test dataset. The classification accuracy of the designed ONN is 82% over the test data. Once the optimized design is achieved, its performance is further verified by 2.5D variational FDTD solver of Lumerical Mode Solution. This verification is done for 100 sample images from MNIST test data set. The prediction accuracy of the designed ONN using FDTD simulator over the examined images is around 80%. Figure 3 shows the x-y electric field distribution in the designed ONN for a sample input image of handwritten digit 2 from the MNIST test data set.

3. Conclusions

In conclusion, an integrated all-optical passive neural network capable of performing various complicated tasks at the speed of light is realized using a multi-layer silicon metaline system on a SOI substrate. Using the integrated photonics technology, the proposed optical neural network has a very few power consumption due to optical transportation of data. Furthermore, it has a small foot-print of 100µm×125µm functioning at 1.55µm.

Acknowledgements

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References


A generalized accurate predictor of nano-optical near fields and far-fields using a deep learning neural network

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Abstract

We present results on a deep learning artificial neural network (ANN) capable of predicting the full near-field and far-field response of plasmonic and dielectric nanostructures. By learning the direct relationship between the geometrical structure and the internal field response, the ANN comes closest to the original problem of solving the electromagnetic wave equation and hence has an opportunity of capturing some of the underlying generalized behaviour. A high level of abstraction is achieved by the ANN including successful inferall of plasmonic antenna effects and magneto-electric resonances of high-index dielectrics, including electromagnetic anapole states and Kerker effects. It also correctly incorporates near-field interparticle coupling and induced near-field chirality in asymmetric dimers. The deep learning approach defines new routes toward very fast optical modelling and enables the data-driven design of nano-optical structures and metasurfaces.

1. Introduction

The ability to control light on length scales shorter than its wavelength has opened up a diverse field of study. Among the tools available are surface plasmon resonances in metal nanostructures and magneto-electric modes in high-index dielectrics. To interpret or predict effects that occur at the interaction of light with photonic nanostructures, Maxwells equations have to be solved rigorously. Most common algorithms are based on a surface or a volume discretization of the nanostructure and possibly its environment. Due to the large size of the resulting systems of equations, nanophotonic simulations are often relatively time-consuming.

Modern computers are powerful machines for solving problems that are hard or even impossible for humans. On the other hand, somewhat surprisingly, many problems trivial for humans, turn out to be actually very hard for a computer. It turns out that using an unconventional approach, problems like image recognition can actually be tackled quite efficiently on computers. The key to such problems lies in searching inspiration in the design of our brains, which lead to so-called artificial neural networks (ANNs). ANNs can be seen as generalized function approximators. They are mathematical functions with thousands to millions of parameters, usually arranged in layers. Because it usually works best with deep networks composed of many successive layers, the field of artificial neural networks is often also referred to as deep learning. Owing to its astonishing capabilities, deep learning is increasingly used in countless applications for scientific data analysis.

The application of deep learning in nanophotonics is taking flight with several recent studies taking advantage of the capabilities of ANNs to learn input-output relationships in order to explore a design space for nanophotonic structures. So far many studies have been successful in correlating abstracted properties, such as optical transmission spectra, to input parameters in a predefined model. Such models are often restrictive as they require a complete re-definition of parameters and retraining for every variation of the design.

In our work, we aim to develop a more generalized approach deriving internal fields from an arbitrary 3D nanophotonic design. This relationship between internal fields and geometry directly follows from Maxwell’s equations and therefore this can be considered the most natural way of mapping nano-optics onto a neural network. Indeed, from the inferred internal fields, all other quantities, including near-fields, far-fields and optical cross-sections, can be derived with relatively small effort.

2. Results

2.1. Definition of the neural network

The ANN used is a three dimensional fully convolutional neural network. Figure 1 shows the network architecture. Our approach translates the typical “U-Net” neural network architecture which has been used successfully in biomedical image segmentation [1]. The network follows an encoder-decoder architecture with residual connections to allow the learning to form identity operations to acceler-
Figure 2: Representative examples from the validation set for silicon (a) and gold (b) nanostructures, showing derived near-field maps, backscattering back-focal plane, scattering patterns and polarization of far-field scattered light.

2.2. Results

We modelled, in two separate datasets, collections of planar gold nanostructures with polygonal shape, and silicon structures consisting of cuboidal blocks of random lateral dimensions, and height of 200nm. Figure 2 shows results obtained for the silicon pillar model and the gold polygons. These examples show a high correlation between the CDA simulations and the inferred values using the ANN. From the internal fields inside the structures, the local near-field maps were calculated as well as the far-field backscattering back focal plane (BFP), scattering patterns and polarization. On the GPU, the trained network delivers its prediction in around 3ms for a planar gold structure and 6ms for a silicon structure, which is 3-5 orders of magnitude faster than conventional numerical simulations.

3. Discussion

In our studies, the ANN has been shown capable of predicting correctly many features of the optical response, including near-field interactions, coupling-induced near-field chirality, magneto-electric scattering resonances including Kerker effects and anapole modes. The neural network approach has achieved a level of abstraction that goes far beyond a simple fitting function, and indicates that the ANN has captured some general aspects of the underlying physical model (i.e. Maxwell’s equations). We have seen a capability of extrapolating outside the trained parameter space, including structures with sizes that were larger in size, as well as shapes previously unseen by the ANN (i.e. cylindrical shaped blocks).

Ongoing work is aimed at further expanding the framework to include more flexibility in design, such as including arbitrary dielectric functions, arbitrary angles of incidence, near-field sources, and broadband spectral response. Of particular interest would be the development of new applications of our ANN approach for the inverse design of photonic nanostructures and metasurfaces.

4. Conclusions

We have demonstrated that a data-driven approach to nanophotonic design is possible using a neural network that is capable of deriving internal optical fields for arbitrary three dimensional structures. The model captures the full complex field distributions including retardation and has been shown to give very good agreement for a large percentage of geometries. This work opens up new direction in neural network based design of nano-optics and metasurfaces.

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References

Deep Learning Approach for the Enhanced Light-Matter Interactions in Dielectric Nanostructures

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Abstract
In this paper, we utilize a deep-learning approach for obtaining high-quality factor (high-Q) resonances with desired characteristics, such as linewidth, amplitude, and spectral position. We exploit such high-Q resonances for the enhanced light-matter interaction in nonlinear optical metasurfaces and optomechanical vibrations, simultaneously.

1. Introduction
Metasurfaces are thin and flat arrays of subwavelength nanoparticles, enabling control over the polarization, phase, amplitude, and dispersion of light [1]. They can be used for light emission, detection, modulation, control and/or amplification at the nanoscale. In recent years, metasurfaces have been a subject of undergoing intense study as their optical properties can be adapted to a diverse set of applications, including superlenses, tunable images, holograms, etc [1, 2]. High-refractive-index dielectric metasurfaces provide a powerful platform for controlling light that can go beyond plasmonics, as they cause negligible losses as compared with plasmonic metasurfaces. Dielectric materials offer unique ability to efficiently manipulate light at the nanoscale based on the simultaneous excitation and control over the optically induced electric and magnetic Mie-type resonances. Resonant dielectric metasurfaces with high-quality factor (high-Q) resonances, in particular, are of significant interests due to their possibilities to strongly enhance the electromagnetic near-fields and boost the light-matter interactions at the nanoscale. It will facilitate various nanophotonics applications, such as enhanced nonlinear photon generations, optical sensing, optoacoustic vibrations as well as narrowband filtering.

Designing metasurfaces with high-Q resonances are usually achieved via continuous parameters tuning, with limited control on the linewidth, amplitude, and spectral positions. Currently, one of the typical approaches for designing metasurfaces with high-Q resonance is based on direct optimization of one or two parameters via brute-force simulations. Recently, deep learning approaches, based on the artificial neural networks (ANNs), have emerged as a revolutionary and robust methodology in nanophotonics.

As a (non-unique) example, we have targeted toroidal dipoles, due to their promising applications in the formation of anapole states and electromagnetic energy localization. We investigate the non-radiating toroidal dipole supported by two parallel silicon bars, as the building blocks of the metasurface.

The proposed deep-learning-assisted inverse approach is used to obtain a bi-functional metasurface dealing with photons and phonons, simultaneously [3, 4, 5]. Photon-photon conversions, so-called nonlinear nanophotonics is at the heart of modern macroscopic optics, including lasers, sensors, imaging and information technology.

Here, by using the deep-learning-assisted inverse approach we design and fabricate a single optoacoustic metasurface that enhances third-harmonic generation intensity for 400+ folds and optomechanical mode excitations for 100+ folds, concurrently, all through a designed high-Q resonance, associated with a strong electric near-field enhancement. The inverse design approach proposed in this paper is extendable to other characteristics and applications of metasurfaces and significantly circumvents the time-consuming, case-by-case numerical models in conventional electromagnetic nanostructure designs.

2. Discussion
To obtain the initial high-Q resonances, we have defined the building blocks of metasurfaces to be two identical silicon nanobars with width \( w \), length \( L \) and the offset \( x_0 \), which is the distance between the center of the two bars fabricated on a glass substrate, as shown in Figure 1. It is worth mentioning that there is a large variety of other geometries, demonstrated earlier for generating high-Q resonances. Interestingly, due to the \( C_2 \) symmetry of our sub-diffractive system, the toroidal dipole (TD) and MQ do not contribute to the far-field radiation along the \( z \)-direction. The far-field optical response is dominated by the ED mode \( p_y \). The non-radiating TD mode is a symmetry-protected BIC, where the ED mode \( p_y \) plays a role to open a leaky channel and transform this ideal BIC into quasi-BIC with...
Figure 1: (a) Top: Schematics of the silicon nanobars metasurface (top left), and its unit cell (top right); Bottom: Calculated transmission spectrum of the metasurface with structural parameters $w = 316$ nm, $L = 580$ nm, $x_0 = 189$ nm. (b) Spherical multipolar structure of the metasurface. (c) Evolution of the training loss for the inverse-design model network. (d) Comparison of the spectra between the NN approximation and the input.

a finite Q-factor. Unlike the MD-BIC studied before where geometrical asymmetry is introduced to open a leaky channel, here the leaky channel, i.e., the excitation of ED mode $p_y$, can be formed directly by properly choosing the structural sizes of the symmetric nanobars. Owing to the non-radiating nature of the dominant resonance – TD mode, a clear enhancement of the stored electric energy inside the nanobars is observed.

Another advantage of high-Q resonances is that the particular electric field distributions can also facilitate the optomechanical vibration process. We further calculate the spectral densities for different pump wavelengths. There is a significant peak with the frequency of 12 GHz for $D_x$ (9.5 GHz for $D_y$) appears for wavelength at 1500 nm, due to the excitation of TD BIC state at the optical pump. The excitation strength of optomechanical mode decreases dramatically when the optical pump is away from the TD BIC state. We then estimate the feedback of the mechanical vibration on the resonant optical response. Based on the transient vibration. Utilizing the high-quality TD BIC state, up to 4.5% modulation of the transmission near the resonance can be expected when using a pulse laser with peak intensity $50$ GW/cm$^2$ through the radiation force on the silicon nanostructures. These results suggest new opportunities for optomechanical applications such as light modulation and nanosensing with nanostructures.

3. Conclusions

To summarize, utilizing machine learning approach, we have demonstrated the inverse design of high-quality Fano resonant metasurfaces composed of two nanobars with scalable characteristics including the spectral position, line width and amplitude of the transmission. The Fano resonance is originated from the TD-BIC state, featuring a strong near-field enhancement and intense electric energy localized inside the nanobars. We further employ these metasurfaces to simultaneously enhance photon-photon and photon-phonon interactions and achieving 400+ folds THG enhancement and 100+ folds enhancement for optomechanical vibrations. Our proposed scalable metasurfaces suggest new opportunities to control and enhance light-matter interactions, showing promising applications for realizing optoacoustic nonlinear metasurfaces.

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References


Inverse design of one-dimensional multilayer structure by artificial neural network

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Abstract

We propose new method of artificial neural network (ANN) training for inverse design of multilayer structures. The ANN directly learns to predict parameters of structures by target reflection spectrum. The transfer matrix method is employed during ANN training to overcome the issue of non-unique inverse problem solution. We compare the target spectrum with spectrum of structure predicted by ANN during the training process. Our ANN is able to design structures with a target spectrum with high fidelity.

1. Introduction

Nanophotonics devices provide sophisticated functionalities through material structuring on the micro- and nanoscale. State-of-the-art fabrication technologies provide unprecedented control over parameters of the patterned structures. As structural complexity grows, the design process becomes more challenging and time-consuming because it requires the solution of the inverse problem. There are several numerical approaches[1]. However, most of them are iterative and consequently computationally expensive. Recently a data-driven approach based on artificial neural networks (ANNs) is shown to be promising for inverse design[2, 3].

ANNs are used in one of two ways. First method is training ANN to predict electromagnetic response by parameters of the structure. In this case ANN replaces computationally expensive simulation and boost the speed of standard optimization methods[3, 4, 5]. Second method is training ANN to predict structure parameters by target response. The main challenge in second approach is uniqueness of the inverse problem solution which leads to poor ANN convergence. In order to overcome this obstacle, tandem ANNs were proposed [2, 6]. Tandem ANNs require training of two ANN, one for forward problem solution and the other for inverse problem. Here we propose a method of on-demand inverse design of one-dimensional multilayer structures using only one ANN. These simple yet versatile structures have a lot of applications, including narrow- and broadband filters, nonlinear optics and analog computing.

2. Results

We consider a multilayer structure consisting of 15 alternating SiO\textsubscript{2} and Ta\textsubscript{2}O\textsubscript{5} layers deposited on a glass substrate. The first layer is SiO\textsubscript{2}. The structure can be represented by an array \( D = [d_1, d_2, \ldots, d_{15}] \), where \( d_i \) is the thickness of \( i \)-th layer starting from the glass. The thickness of layers varies from \( d_{\text{min}} = 0 \) to \( d_{\text{max}} = 350 \) nm. The incident light is TE-polarized with a wavelength of \( \lambda = 780 \) nm. Our goal is designing a multilayer structure with predefined reflection spectrum for angles of incidence ranging from 20 to 30 degrees. Spectrum is discretized by 20 points and target response is represented by array \( R \) of length of 40 (20 points for real part, 20 points for imaginary part). We choose real and imaginary part of reflection spectrum rather than phase and magnitude since it improves phase prediction accuracy of the ANN[4].

To train ANN, we firstly generated training and test dataset with custom program implementing the transfer matrix method (TMM). In the calculations, refractive indices of SiO\textsubscript{2} and Ta\textsubscript{2}O\textsubscript{5} and glass are set to be 1.45, 2.08, 1.52, respectively. Datasets consist of reflection spectrum arrays \( R \) of randomly generated structure. It guarantees that target spectra are physically realizable. Thickness arrays \( D \) of random structures are not used in any way in the ANN training process. Training dataset contains 400 000 spectra, test dataset – 40 000. Datasets generation takes less than 1 minute on desktop computer (Intel(R) Core(TM) i5-4200 CPU @ 1.60 GHz, 6 GB of RAM). Such a high speed is the result of optimized program code.

We use a fully connected network consisting of 8 layers. Its architecture can be denoted as 40-50-100-100-100-100-15, where number is an amount of neurons in each layer. The input of the ANN is target \( R \) array and the output is normalized array \( D_{\text{norm}} \) with layer thicknesses of designed structure. Array \( D \) can then be calculated \( D = d_{\text{max}} \ast D_{\text{norm}} \). The activation function of all layers except the last one is rectified linear unit activation function (RELU). The activation function of last layer is sigmoid function and consequently the ANN output lies in range from 0 to 1. In order to solve the uniqueness problem, ANN training is performed using solely \( R \) arrays. For this purpose reflection spectrum \( R_{\text{pred}} \) of ANN output \( D \) is calculated by the TMM first, and then the mean squared error (MSE) between target spectrum \( R \) and \( R_{\text{pred}} \) is estimated. Training is done by minimizing MSE. The TMM is naturally fit in the ANN training process since it is based on matrix multiplication and allows implementation of error back propagation – indispensable tools for network training. The ANN was implemented using PyTorch framework. We also
had to rewrite the TMM program using this framework. We use Adam optimization algorithm with learning rate 0.01 decaying by 0.1 every 300 epochs during training. Batch size was set to be 20000. The training takes about 15 hours. Although ANN training is time-consuming, it is a one-time cost. After 900 epochs MSE for the train and test dataset dropped to 5.6e-5 and 5.8e-5, respectively. The ANN is able to generate structures with target spectrum with high fidelity. Fig. 1a demonstrates the dependence of magnitude of reflection spectrum of random sample from test dataset and of structure generated by ANN on angle of incidence $\alpha$. In fig. 1b the phase of reflection coefficient of two structures is shown. Even though the generated structure produce the spectrum close to target, it is completely different from the one used for test dataset generation:

$$D_{\text{ANN}} = [184.5, 158.4, 172.8, 155.5, 185.1, 201.6, 195.4, 177.8, 196.2, 205.5, 181.2, 172.4, 202.2, 138.3, 142.6]$$

$$D_{\text{test}} = [43, 83, 308, 276, 58, 170, 213, 218, 316, 138, 1, 9, 306, 338, 273],$$

where $D_{\text{ANN}}$ is thickness array generated by the ANN, $D_{\text{test}}$ is the thickness array used to calculate target reflection spectrum. This feature once again demonstrates the uniqueness property of inverse problem solution.

3. Conclusions

In this work we propose a method for training the ANN to inverse design of multilayer structure. The ANN is trained solely on target reflection spectrum without knowledge about parameters of the structure producing this response. The ANN training is based on the TMM. The ANN can generate structures with reflection spectrum close to target one. Our approach can be extended to other systems and paves the way to on-demand design of novel nanophotonics devices with complex functionalities.

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References


Deep Neural Networks for the Prediction of the Optical Properties and the Design of Metamaterials

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Abstract
We will present our work on using deep neural networks for the prediction of the optical properties of free-form nanophotonic structures and for their inverse design. We designed neural networks and created training data, which were labelled with the respective optical properties and the degree of manufacturability. Furthermore, a cGAN network with 5 neural networks was developed to overcome problems with non-uniqueness and mode collapse, and to increase the experimental feasibility of the generated structures.

1. Introduction
In recent years, research on the light-matter interaction of artificially tailored subwavelength materials has led to numerous discoveries such as the ability to engineer optical near fields, localized surface plasmon resonances, strong enhancement of quantum emitter luminescence, and the emergence of nonlinear optical phenomena. These effects can be used to realize various novel applications like all-optical devices [1, 2, 3] that use light to solve, e.g., integral equations, integrated quantum optics devices [4] or for metamaterials [5, 6] and thin metasurfaces that can replace otherwise bulky lenses [7] or mirrors in a multitude of optical devices [8]. This contribution focuses on the computational and methodological difficulties associated with the evaluation of the optical properties of a given metasurface unit cell and on the inverse design of a metasurface given a set of desired optical properties. Deep artificial neural networks can have significant advantages compared to traditional calculation methods in these fields when they are applied carefully [9, 10]. We will first discuss how we use a convolutional neural network (CNN) to calculate the optical properties of an arbitrary metasurface unit cell. Subsequently, we discuss a classifier network and a conditional generative adversarial network (cGAN) to perform the inverse design of metasurface unit cells.

Figure 1: The forward model, which is schematically depicted in this figure, approximates the S parameters of a given metasurface unit cell. Clockwise: (a) Rendered illustration of unit cell. (b) Grid representation of the lithographic mask of the unit cell. (c) Schematic architecture of the forward model. (d) S parameters.

2. Prediction of optical properties
We first focus on the prediction of the optical properties of metasurfaces. We constructed a forward model \( \mathcal{F} \) that approximates the optical properties (S parameters \( S \)) of a given grid representing a metamaterials unit cell (\( g \)):

\[
\mathcal{F}[g] \approx S
\]

This model is useful to bypass time-consuming full-wave simulations, but more importantly it is an essential part of the inverse design method we will discuss later, where it is used as a surrogate model.

Here, we decided to use a binary grid representing a lithographic mask in the fabrication of a periodic metasurface, to make our approach as general as possible. A CNN was developed to approximate the S parameters of the respective unit cell. The network approximates the four S parameters and additionally the sum of all intensities for 41 frequencies. In order to create the training and validation data for the CNN, a large number of semi-random grids in a predefined height range were created and then processed by a finite ele-
The discriminator takes the grids as input and analyzes them. In theory, this would be enough to train the discriminator. However, it is a difficult task for a discriminator to differentiate between grids produced by the generator and grids from the data set, while at the same time evaluating whether the grids have the desired optical properties and obey the required feasibility constraints. In addition, like other GANs, this kind of cGAN with continuous labels is susceptible to mode collapse. We will show how these two problems can be solved with “advisor” networks and with an encoder network, respectively.

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References


Structured and topological photonic fields
Field Distributions and Atom Trapping in Focused Axially-Shifted Counter-Propagating light Beams

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Abstract

We highlight the properties and the physics of a special kind of structured light, namely when two counter-propagating Laguerre-Gaussian optical beams interfere with their focal planes shifted axially by a finite distance d. We distinguish between two different situations: the back-to-back (d<0) and face-to-face (d>0) cases and show how these lead to finite ring lattices, Ferris-wheels and conveyor belts between the focal planes. Furthermore, even in the case of shifted Gaussian beams a new all-optical atom trapping environment is shown to arise due solely to the scattering force on atoms near resonance when the beam waist are of sub-wavelength dimensions. Our findings are discussed with reference to sodium atoms.

1. Introduction

The discovery of light beams carrying orbital angular momentum (so-called twisted light beams) and their realization using novel experimental techniques such as spiral phase plates or computer-generated holograms have led to new applications involving the optical trapping and cooling of atoms, free-space communications, optical cryptography and in general novel light-matter interactions. Not only light beams have been shown to carry OAM but also matter waves as, for example, beams of electrons, neutrons or even neutral atoms and ions. Theoretical and experimental analysis on the effects of twisted light beams on atoms have shown that the OAM of light can be used as a tool to bring out different degree of translation and rotation of atoms depending on the OAM contents, which led to the possibility of using twisted light in the field of manipulation of atoms. The superposition of twisted light beams, namely co- or counter-propagating axial-shifting beams, involves strong interference effects leading to optical lattices, Ferris wheels, new kinds of optical trapping [1]. We have recently emphasized the optical environment in which axially-shifted counter-propagating twisted or untwisted light beams are set up [2]. Here we focus on such multiple beams which are strongly focused.

This talk intends to highlight some striking features of interference of strongly focused counter-propagating twisted light beams. Strong focusing, enhances contributions from the Gouy and curvature phases in interactions with atoms and for beam waists in the sub-wavelength regime value even in the case of untwisted beams the scattering force produces complete atom trapping. We show that axial-shifting as a parameter plays an important role in the generation of the interference patterns and the characters of the optical forces acting on the atom.

2. Axial-shifting induced optical forces

If the beam waist and wavelength are of the same order, it is possible to observe novel properties of the scattering and dipole forces and by virtue of the interference effects, new kinds of optical trapping regions and optical lattices are generated.

2.1. Dipole Force due to the interference effect

Figure 1: The dipole force in-plane distribution due to counter-propagating doughnut beams with focal planes coinciding at z=d/2. Here the winding numbers are both ℓ=2
and this leads to the four lobes pattern shown with arrows representing the local direction of the force.

Figure 1 displays the dipole force arising from the superposition of two counter-propagating doughnut beams for beam waist $w_0 = \lambda$, winding number $\ell = 2$ axial shift $d = 3w_0$ and the plot is in the plane $z = d/2$.

From figure 1, we can conclude that by changing the beam waist, the axial shift and the winding number we are able to change the characteristics of the dipole force. By reducing the beam waist to values as low as sub-wavelength values, we can change the directions and magnitudes of the local force vectors. The change in the shifting parameter $d$ (for example $d < 0$) leads to the change in bright and dark regions which means that the locations of the trapping potentials will be reversed. OAM varies the number of lobes and change the size of the dark region.

![Figure 2: The dipole force distribution evaluated in the plane $z = 2d$. The parameters are the same as those in Fig. 1.](image)

Figure 2 shows the dipole force distribution in the plane $z = 2d$. The spiral geometry is due to the interference effects between inner and outer rings of the beams. If the $z$ plane is chosen as larger than $3d$, we find that the doughnut rings completely separated from each other. Note that the direction of the force vectors are towards the center for the inner ring while those in the region of the outer rings have outward directions.

2.2. Scattering Force and Dipole Force when omitting interference effects

The scattering (or dissipative force) is a result of the gradient of the phase function of Laguerre-Gaussian beam. The scattering force can be evaluated using the same parameters used in the dipole force. In order to elucidate the effects of the shifting of the focal planes we concentrate on the independent beam approximation, where forces, both dipole forces and scattering forces from individual beams simply add. Once more we choose $\ell_1 = -\ell_2$.

![Figure 3: Total of scattering and dipole forces obtained from the superposition of two counter-propagating doughnut beams where $\ell_1 = -\ell_2$. Top, middle and bottom rows indicate the force vector distributions $z = d/2$, $z = 0$ and $z = d/2$, respectively.](image)

The results for this case are shown in Figure 3. The inner ring of the vectors are due to the scattering force, while the outer ring are due to the dipole force.

3. Conclusions

We have explored the field distributions and the optical forces acting on atoms due to interaction with counter-propagating axially-shifted doughnut beams. In view of the fact that the recoil energy of Na atoms is in the scale of $10^{-29}$ J, we have found using realistic parameters that the corresponding trapping potential due to the scattering force alone in the x-y plane to be sufficiently deep to trap Na atoms. By varying the OAM content, the beam width and the focal plane shift $d$, it is possible to design and modify the geometry of the optical forces to attain desirable all-optical trapping potentials for use where single atoms and ions are needed for quantum technology applications.

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K. Koksal., V. E. Lembessis, J. Yuan, M. Babiker, All optical scattering force control of atoms - beyond the Optical Earnshaw Theorem, submitted to Nature Photonics
Three-dimensional vectorial holography based on machine-learning inverse design

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Abstract

Conventional optical holography can address only the amplitude and phase information of an optical beam, leaving the 3D vectorial feature of light inaccessible. We demonstrate 3D vectorial holography where an arbitrary 3D vectorial field distribution on a wavefront can be precisely reconstructed using the machine-learning inverse design based on multilayer-perception artificial neural networks. Such 3D vectorial holography allows the lensless reconstruction of a 3D vectorial holographic image with near-unity 3D polarization purity. Holographic information can thus be encoded and encrypted on the wavefront of a 3D vectorial field.

1. Introduction

Optical holography, which allows the reconstruction of both the amplitude and phase information of a 3D image of an object, has propelled many new technologies including optical displays, data storage, optical trapping, holographic fabrication, pattern recognition, and all-optical machine learning. The 3D vectorial nature of light is fundamentally important to the understanding of the light-matter interaction [1-3]. It should also play a significant role in holographic optical trapping [4], high-resolution imaging [5-8], and high-capacity data storage [9]. However, the 3D vectorial information of a holographic image has been inaccessible, primarily due to the negligence of the vectorial nature of light in conventional digital holography. Mathematically, embedding the vectorial information in a digital hologram requires an inverse solution to a complex 3D vectorial field distribution; however, such a complexity has remained a challenging endeavor to 3D vectorial holography.

Machine-learning inverse design has revolutionized on-demand design of structures and devices including functional proteins in biology [10], complex materials in chemical physics [11], bandgap structures in solid-state physics [12], and photonic structures with previously unattainable functionalities and performance [13]. As one of the most successful machine-learning methods, artificial neural networks inspired by the brain architecture has been demonstrated to be an accurate and time-efficient approach to solving complex inverse problems in functional nanostructure design [14], machine learning microscopy and imaging [15], detection of quantum states [16], and all-optical machine learning [17].

2. Results

Here, we demonstrate an entirely new concept of 3D vectorial holography through the use of machine-learning inverse design based on multilayer-perception artificial neural networks (MANNs) for the time-efficient and accurate reconstruction of a 3D vectorial holographic image. The principle of 3D vectorial holography is depicted in Fig. 1, where a vectorial hologram with two digital functions of a phase hologram and a 2D vector field distribution is designed to reconstruct a 3D vectorial holographic image (kangaroo) (Fig. 1A). As such, each pixel in the vectorial holographic image can be represented by a 3D vectorial field. To create an arbitrary 3D vectorial field with high purity, the MANNs are trained to statistically learn the relationship between a given 3D vectorial field in the image space and the 2D vector field distribution in the hologram plane (Fig. 1B). Notably, the longitudinal (E₃) component of a 3D vectorial field is achieved by a large-angle Fourier-transform (FT) holographic lens embedded in the digital phase hologram. As a result, the wavefront leaving the vectorial hologram features a broad angular spectrum and transforms onto the sphere weighted by a vectorial distribution. This vectorially weighted Ewald sphere plays a key role in the lensless reconstruction of a 3D vectorial holographic image for floating display with an ultrawide viewing angle up to 94 degrees.
Our demonstrated 3D vectorial holography provides an artificial-intelligence-enabled holographic paradigm for harnessing the vectorial nature of light, enabling new machine-learning strategies for holographic 3D vectorial fields multiplexing in display and nanofabrication, optical trapping and localization, and superresolution microscopy and imaging. In particular, the demonstrated holographic 3D vectorial fields multiplexing has significant implications for the fundamental understanding of the light-matter interaction, which may provide a new degree of freedom in Mobius strips, phase singularities, and optical vortex knots. In addition to fundamental impacts, 3D vectorial holography opens new avenues to widespread applications such as holographic trap display and multi-dimensional data storage, optical trapping and localization, machine-learning microscopy and imaging systems. High-resolution direct laser writing of a vectorial hologram, demonstrated in this work, is a scalable technology, and thereby could further be combined with active materials for the artificial-intelligence-enabled floating display of 3D vectorial holographic images. It provides an unprecedented opportunity to encode and encrypt holographic information onto 3D vectorial fields, which is previously inaccessible but of great importance for increasing multiplexing capacity in holography and for protecting optical information.

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References

The physics of the magnetoelectric near fields

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Abstract
The surface limiting a solid body locally modifies the physical properties of materials. A continuous variation of field structure across the interfaces defines the near field, which is considered as the extension of the field existing inside the material to the outside region. In a case of near fields of dielectric materials, one observes the evanescent wave character of the fields with continuous variation of field amplitudes and energies across the interfaces. In a case of a material with magnetoelectric (ME) properties, along with the question of variation of field amplitudes, questions also arise of variation of field phases and angular-momentum conservation across the interfaces.

1. Introduction
In close proximity to the surface of various materials, there are different kinds of near fields [1]. For usual (non-ME) material structures, we can distinguish two kinds of the electromagnetic (EM) near fields: (a) near fields originated from EM wave resonances and (b) near fields originated from dipole-carrying resonances. The former fields, abbreviated as EM NFs, are obtained based on the full-Maxwell-equation solutions with use of Mie theory. The latter fields, abbreviated as DC NFs, are observed when the electric or magnetic dipole-carrying oscillations (such, for example, as surface plasmons and magnons) take place. Notably, in accordance with Mie theory one can observe EM NFs with magnetic responses originated from small nonmagnetic dielectric resonators, both in microwaves and optics. In a case of DC NFs, strong coupling of EM waves with electric or magnetic dipole-carrying excitations, called polaritons, occur. There is the avoided-crossing coupling between the photon and the dipolar oscillation. Semiclassically, polaritons are described using Maxwell equations and constitutive relations that include the frequency dependent response functions. Quantum mechanically, polaritons are described as hybrid collective excitations that are linear superpositions of matter collective excitations and photons. There are the effects of interaction between real and virtual photons. Importantly, the spatial scale of the DC NFs is much smaller than the spatial scale of the EM NFs in the same frequency range. Due to the strong coupling of EM waves with dipole-carrying excitations and temporal dispersion of the material, polaritons display enhanced field localization to surfaces and edges. The properties of vacuum near fields originated from a small non-ME (dielectric or magnetic) sample become evident when this sample has sizes significantly smaller than the EM wavelength in all three spatial dimensions. The matter of fact is that near such a scatter we can only measure the electric \( E \) or the magnetic field \( H \) with accuracy. As volumes smaller than the wavelength are probed, measurements of EM energy become uncertain, highlighting the difficulty with performing measurements in this regime. There is Heisenberg’s uncertainty principle binding \( E \) and \( H \) of the EM wave [2, 3]. Talking now about the near fields of ME-material structures – the ME fields – we are dealing with the effects of strong coupling of EM waves with specific dipole-carrying excitations, called electromagnons. The electromagnons are considered as fundamental excitations that exhibit both electric and magnetic dipole moments. In case of a subwavelength ME sample, the near-field structures are dominated by two types of the fields: the electric and magnetic fields, which are mutually coupled due to the material properties. When the violation of the invariances under space reflection parity and time inversion are necessary conditions for the emergence of the ME effect, the same symmetry properties should be observed for the near fields – the ME near fields. Due to PT symmetry of ME crystals, the ME near fields of a subwavelength sample should be characterized by a certain pseudoscalar parameter. Evidently, such a structure of ME near fields is beyond the frames of the Maxwell theory description [4, 5].

2. ME near fields created by MDM resonances
ME near fields can be considered as quantized states of dipole-dipole magnons in subwavelength domains of ME materials. Such quantized states are well modeled by spectral characteristics of magnetic-dipolar-mode (MDM) oscillations [or magnetostatic (MS) oscillations] observed in confined ferromagnetic-insulator structures. Based on the spectral analysis, one can show that ME near fields are PT symmetric. At the MDM resonances, one observes the field helicity and vortices of active power flows. There are also the reactive power flows (see Fig. 1). The properties of ME near fields define unique topological characteristics of polaritons (see Fig. 2) [6 – 8].

Quantized ME fields arising from nonhomogeneous ferromagnetic resonances with spin-orbit effect, suggest a conceptually new microwave functionality for material
sensing. Visualization of the ME states requires an experimental technique that is based on an effective coupling to the violation of spatial as well as temporal inversion symmetry.

Figure 1: Helicity density and active and reactive power flows of ME near fields above and below a ferrite disk at the MDM resonance. (a) An upward directed bias magnetic field; (b) a downward directed bias magnetic field. The active and reactive power flows are mutually perpendicular.

Figure 2: The pictures of the E-field structures on a vacuum plane above a ferrite disk. (a) Wavefront at frequency far from the MDM resonance; (b) wavefront at the MDM resonance frequency.

3. Conclusion

ME near fields of MDM ferrite disk are characterized by in-plane power-flow vortices and the helicity parameters. The field amplitudes decrease exponentially in direction of a normal of the disk. The structure of a ME near field is PT symmetric. With such a topological structure of ME near fields, one observes two kinds of polaritons: the right-hand ME polaritons and the left-hand ME polaritons. When the external microwave structure is geometrically symmetrical, the two types of ME polaritons are indistinguishable. Otherwise, different microwave responses can be observed depending on the direction of the bias magnetic field. These properties of ME polaritons have been used for microwave chirality discrimination in enantiomeric liquids [9].

References


Photonic simulation of Rashba-Dresselhaus spin-orbit coupling in a tunable birefringent cavity

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Abstract

Rashba and Dresselhaus effects well known in semiconductor physics have inspired the field of spintronics by providing a means of spin manipulation. In this communication we will demonstrate how these phenomena can be simulated in a purely photonic system – a birefringent photonic microcavity. Experimental spectra of a tunable liquid-crystal-based device will be presented opening the avenue for novel technical solutions which exploit the analogy between the electron’s spin and photon’s polarization.

1. Introduction

The creation of physical systems which realize preassigned quantum evolution leads to the idea of synthetic Hamiltonians or artificial gauge fields [1] which can mimic or simulate complex quantum mechanical problems. In this paper we propose a new approach to simulate the magnetic field and spin-orbit interaction (SOI) of massive particles with spin using purely bosonic photon field in a cavity containing a uniaxial anisotropic medium. By precise tuning of the effective refractive index we can adiabatically change the coupling between subsequent photonic modes in a form corresponding to the Hamiltonian with Zeeman, Dresselhaus [2] and Bychkov-Rashba [3,4] terms conventionally derived for fermions.

2. Liquid crystal microcavity and reflectivity measurements

A nematic liquid crystalline (LC) medium was enclosed in a planar multimode optical cavity [5,6]. The liquid nature of these materials allows for convenient control of optical properties by relatively weak external electric fields. With the ability to manipulate the permittivity tensor and, therefore, effective refractive indices for different polarizations of light, it is possible to tune the energy splitting between cavity modes of orthogonal polarizations. Schematic structure of the sample is presented in the Fig. 1. Initially, the molecular director is arranged in plane of the sample (xy plane) and with the application of voltage, it tilts in the z direction (Fig 1.b).

![Schematic diagram](image)

Figure 1: Schematic diagram of a the cavity filled with a LC and b of tilting of the optical indicatrix of the LC medium in the cavity.

We measured angle-resolved reflectivity maps (Fig. 2 ) for different voltages applied to the sample. Without external voltage for two perpendicular linear polarizations (H, V) the refractive indices are different (nH and nV), which results with the initial splitting of photonic modes, given by the birefringence of the material (Fig. 2 a). With application of the external voltage we can tune the effective refractive index (n_{eff}) in horizontal (H) direction according to equation:

\[ n_{eff}(U) = \frac{n_H n_e}{\sqrt{n_H^2 \cos^2(\theta(U)) + n_e^2 \sin^2(\theta(U))}} \]  (1)

At a certain voltage applied to the sample in the reflectivity spectrum we observe for a certain voltage (2.46 V) two non-coaxial oppositely circularly polarized parabolas (Fig. 2 b)
3. Discussion

When two linearly polarized modes of different parity are brought into resonance, the SOI effects of light which stem directly from the solutions of Maxwell equations [5] become apparent. Using the approximation of birefringent electromagnetic waveguide one can show that the evolution of the system is described by Rashba-Dresselhaus Hamiltonian:

$$\hat{H}_{\text{exp}} = \frac{\hbar^2 k_x^2}{2m_x} + \frac{\hbar^2 k_y^2}{2m_y} - 2\alpha \hat{\sigma}_z k_y + \frac{1}{2}(E_{x,l} - E_{y,l})\hat{\sigma}_x, \quad (2)$$

where $\hat{\sigma}_l$ Pauli matrix written in the basis of the decoupled circularly polarized cavity modes and $k_l$ is light’s direction of propagation. The Rashba parameter $\alpha$ depends on the properties of LC, the director orientation relative to the plane of the sample, and the cavity thickness. Coupling between the modes can be experimentally traced on the reflectivity maps as a function of the voltage applied to the sample. We can determine the dependence of the energy splitting of the modes as the function of the wave vector. As presented in Fig. 3f the splitting is proportional to the wave vector, as expected for the Rashba-Dresselhaus spin-orbit coupling Hamiltonian (2). The experimentally determined slope give the Rashba-Dresselhaus parameter equal to $\alpha = 31.9 \text{ eV}\cdot\text{Å}$.

4. Conclusions

We proposed and realized a purely bosonic system operating at room temperature, for which we investigated and described the dispersion relation, associated with and previously observed for fermionic systems. The discovery of new phenomena related with the confinement of light in optically anisotropic cavities may enable the implementation of new optoelectronic devices, e.g., optical neural networks and performing neuromorphic calculations. Engineering of spin-orbit synthetic Hamiltonians in cavities opens the way to photonic emulators of quantum Hamiltonians with internal degrees of freedom. Particularly promising is the prospect of creating a unique quantum state of matter – Bose-Einstein condensate. This condensate can be used for quantum calculations and simulations, i.e. solving problems that are too difficult for modern computers. The studied phenomena will open up new possibilities for technical solutions and further scientific discoveries.

Acknowledgements

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References

Compact Meta-Spectrometer for Mobile Applications

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Abstract
We demonstrated an extremely compact and efficient meta-structure-based spectrometer for use in the near-infrared range. The spectrometer consists of a mobile-phone CMOS imager and silicon-nanoposts-embedded dielectric multilayers fabricated directly on top of the imager. The spectrometer shows good transmission and excellent spectral resolutions. In addition, the presence of the metaposts embedded in the dielectric layers greatly simplifies the fabrication process to generate individual spectral channels. It shows promise of integrating compact spectrometers in smartphones for diverse applications.
Metasurface spin-to-orbital angular momentum converters

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Abstract

Creating complex states of structured light from lasers is a venerable topic, initially achieved by amplitude and dynamic phase control, and more recently by geometric phase, the former limited to scalar modes while the latter limited to cylindrically symmetric vector orbital angular momentum (OAM) modes of opposite helicity. Here we report a visible metasurfaces that overcomes these limitations, controlling the full angular momentum of light by arbitrary spin-to-orbit (SO) momentum conversion. We demonstrate beams with independent OAM coupled to user-defined linear or circular polarisation states, all from the same laser. Our nanostructured metasurfaces are compact and power scalable, for the creation of arbitrary angular momentum states of structured light.
High harmonic generation with topological light fields

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Abstract

Results of quantum mechanical calculations of an atomic gas irradiated by three-dimensional topological light fields are presented. The investigation of the high harmonic generation reveals that the generation of topologically protected and polarization-structured light fields in the X(UV) frequency regime is possible with only one driving field.

1. Introduction

High harmonic generation (HHG) using three-dimensional and spatially inhomogeneous electromagnetic vector fields offers new opportunities for producing (X)UV pulses. Optical vortices or vector beams (which are polarized in the transverse plane) may have a strong longitudinal component when appropriately focused. When used as the driver field in the (near) infrared, the interpolar between the longitudinal and the transversal field components determines the properties of the emitted harmonics.

In the laser spot of a radially polarized vector beam (RVB), the field in the outer area of the disk-shaped intensity profile is radially polarized, while in the beam center the field is longitudinal. An important feature of the RVB is a $\pi/2$ phase shifted between the transversal and longitudinal time-oscillating components.

An optical skyrmion has a space-dependent polarization landscape and a phase structure of the orbital part. Hereby, the spatial phase structure is intertwined with the polarization.

We will present our investigations on higher harmonics emitted by an atomic gas irradiated by a tightly focused RVB or an optical skyrmion. While RVB enables the generation of circularly polarized XUV light with minimal divergence (when moving to higher order harmonics), an IR skyrmion generates topologically protected higher harmonics with a rich polarization landscape.

2. Discussion

For illustrations, we run numerical simulations employing a four-cycle long IR (800 nm) radial vector beam with a $\sin^2$ temporal envelope and a fixed peak intensity at the donut rim of $1.6 \times 10^{14}$ W/cm$^2$. The effective beam diameter is one micron. From the quantum mechanically propagated wave functions (of an emitter $i$) we find the time dependent charge and current densities $\rho_i(r,t)$ and $j_i(r,t)$ which yield the radiated vector and scalar potentials $A_i(r_d,t)$ and $\varphi_i(r_d,t)$ at a detector position $r_d$. The total response of an atomic gas is then given by the coherent superposition $\sum_i A_i(r_d,t)$ and $\sum_i \varphi_i(r_d,t)$.

In Figure 1, we present examples for higher harmonics generated in the RVB-driven atomic gas. As shown in panel a), the far-field Poynting vector reveals a cylindrical symmetry and a dark spot in the area around the optical axis, which can be explained by the diminishing intensity of the corresponding magnetic field when $\beta \to 0$. A higher harmonic order results in a tighter radiated beam spot since the axial distance to the intensity peak shrinks.

An important finding is the possibility to generate circularly polarized higher harmonics, as revealed by Figure 1b). Here, the spatially-dependent Stokes parameters of the 13th harmonics are shown for a varying divergence angle (we note that the general behaviour of the $S_1$ persists when considering even higher harmonics). They are defined in terms of the transversal harmonic field component $E^{(n)}_\rho (r)$ (n is the harmonic order) and the longitudinal component $E^{(n)}_z$, i.e., the polarization states refer to a specific $\rho-z$ plane (we note that the whole process is radially symmetric). On the optical axis, all harmonics are strictly linearly polarized, as emphasized by $S_1 = -1$. The reason is a strong longitudinal component similar to the driving field. Increasing the axial stance yields the build-up of $S_3$ while $S_1$ decays, whereas $S_3$ characterizes the degree of circular polarization. Consequently, the polarization state changes from linear (in the z-direction) to circular to linear (in plane), meaning a transition into radial polarization. Further, a high degree of ellipticity is concentrated.

Figure 1: RVB-driven HHG process. a) Divergence with increasing harmonic order. b) Stokes parameters of one selected higher harmonic.
around the maximum of the energy flux (Poynting vector), which is presented by the black, dashed curve. For an optical skyrmion as a driver field the spin angular momentum density reads $\sigma = \epsilon (E_{OS} \times A_{OS})$ and is presented in Fig. 2a where the associated unit vector $m_{OS} = \sigma / |\sigma|$ is depicted. The vector changes continuously from out-of-plane to in-plane to out-of-plane in a periodic manner when the axial distance is increased. Further, the field is topologically protected, i.e., in analogy to the magnetic skyrmion, we may define
\[ n_{OS} = \frac{1}{4\pi} \int dA \ m_{OS} \cdot \left[ \partial_x m_{OS} \times \partial_y m_{OS} \right] = \pm 1. \] (1)

Astonishingly, all radiated harmonics have a similar spin angular momentum texture and reveal topological protection. Application of an optical skyrmion as the HHG driver allows the generation of polarization structured XUV light fields, where all possible polarization states are transferred coherently and phase-locked into the high-frequency regime. Panels b-d) of Figure 2 show the normalized and spatially resolved Stokes parameter of the fifth harmonic as a representative example. Similar to the fundamental field, the polarization landscape is highly involved, meaning that all polarization states and periodical structures can be found. All harmonics are fully polarized as we proofed numerically that $S_1^2 + S_2^2 + S_3^2 = 1$. As a consequence, moving the position of the observer slightly could alter the polarization state drastically.

A key finding is the possibility of generating circularly polarized higher harmonics, as revealed in Fig. 2d). We find circularly polarized ring-like structures around the optical axis. The handedness changes periodically when increasing the distance to the optical axis. Therefore, the HHG process driven by an optical skyrmion is an effective alternative method for generating circularly polarized XUV harmonics.

3. Conclusions
We investigated the HHG process driven by three-dimensional topological light fields. The spin and orbital properties of the driving field enable the generation of polarization structured XUV light fields. Moreover, the topological index of the driving field is a conserved quantity in HHG, meaning the topological properties are transferred into the higher frequency regime.

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References
There is now considerable activity and much interest in optical and electron vortex waves both of which continue to be researched theoretically and experimentally. There is also growing interest in other matter vortex waves. Atoms, positrons, neutrons and neutrinos are among those currently being considered. Electron vortex waves have already been created and experimentally investigated in electron microscopes [1, 2] and have been shown to be similar to but they are also rather different from optical vortex beams [3]. Neutrons were next to be explored for the possibility of generating neutron vortex states [4]. Research on matter vortices now seems to be heading towards spanning a number of disciplines, with their use now contemplated in various areas, including biophysics and nuclear and particle physics.

Earlier proposals of matter vortices other than electrons had involved theoretical studies which focused solely on neutral atoms as possible candidates for the generation of atom vortex beam states carrying orbital angular momentum [5]. These proposals appeared particularly persuasive in view of the extensive work on the well-developed field of atom optics in which atomic beams were passed through optical diffractive elements. Very recent experimental work appears to have been successful in generating atom vortex waves. The article by Alon Luski et al [6] reported the creation of the first atom vortex beams as well as those of molecules. Their atom vortex beams emerged on diffracting neutral helium beams of supersonic speeds on binary transmission gratings.

The ability to generate optical vortex beams as well as matter beams, particularly neutral atoms suggests scenarios in which vortex atoms can be made to interact with vortex photons. These scenarios promise a wealth of new physics, most notably exchange of orbital angular momentum in multipolar interactions, the effects of optical spin and optical spin-orbit coupling where the longitudinal field component comes into play.

This talk will outline the general concepts underlying particle beam generation. It then surveys matter particles including composites such as neutral atoms and small and large molecules which can be subject to quantum diffraction. Fundamental vortex properties, namely linear and orbital angular momentum contents, spin and associated electromagnetic fields as well as mechanical and vortex multipolar interactions are discussed. Several features involving spin-orbit coupling, chiral atom trapping potentials and angular momentum exchange with matter are highlighted. Two sets of our recent results highlight the chiral effects of spin-orbit coupling on the trapping potentials of neutral atoms in the presence of the longitudinal field of Laguerre-Gaussian (LG) doughnut beams $LG_{\ell=\pm 1, p=0}$. Figures 1 and 2 explain how the atom experiences different trapping potentials for circularly polarised single and bi-chromatic LG doughnut beams which differ only in the sign of their winding number $\ell$. The spin-orbit interaction and the inclusion of the longitudinal field components are crucial in this context [7].

FIG. 1: (a) The optical dipole potential energy for right-handed circular polarization. Solid line represents the case where $\ell = +1$, dashed curve represents the case where $\ell = -1$; (b) The optical dipole potential energy for left-handed circular polarization. Solid line represents the case where $\ell = -1$, dashed curve represents the case where $\ell = +1$. In both (a) and (b) the dotted line shows the optical dipole potential energy without taking into account the contribution of the spin-orbit term. The insets to the figures show the potential energies of the solid curves and their projections in the focal plane. These insets should be interchanged for the dashed curves. In all plots the potential energy is in recoil energy units while the radial distances are in LG beam waist units. For details see [7]

FIG. 2: (a) The optical dipole potential energy for a bi-chromatic field with $\ell = 1$ (solid line). The plot is inverted if $\ell = -1$ (dashed line). (b) Optical dipole potential energy for a bi-chromatic field with $\ell = 5$ (solid line). This plot is inverted if $\ell = -5$. In both plots the potentials are given in recoil energy units while the radial distances are in LG beam waist units. For details see [7]
Structured ultrafast high-harmonic pulses

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Abstract

Coherent extreme-ultraviolet/soft x-ray pulses structured in their temporal (attosecond), spectral (line spacing) and angular momentum (polarization and topological charge) properties is nowadays possible thanks to high harmonic generation. In this talk we review our recent work in the generation and control of ultrafast structured harmonic pulses through the use of infrared driving beams with custom angular momentum properties.

Whereas angular momentum can be routinely transferred to visible/infrared (IR) light beams using waveplates, or spatial light modulators, among other techniques, it becomes a lot harder in the extreme-ultraviolet (EUV)/x-ray regimes, where those techniques are inefficient. This challenging goal is very much worth the effort: imprinting spin (SAM) and/or orbital (OAM) angular momentum into the EUV/x-ray regimes will bring the applications of structured light down to the nanometric and ultrafast scales.

Among other x-ray sources such as x-ray free electron lasers or plasma-based soft x-ray lasers, high-harmonic generation (HHG) stands as a robust mechanism to generate highly spatially and temporally coherent radiation from the extreme-ultraviolet (EUV) to the soft x-ray regimes [1], with exquisite temporal accuracy in the attosecond regime [2]. Remarkably, such control is acquired through a highly nonlinear up-conversion process, where the properties of an infrared driving field are mapped into high-frequency harmonics. However, such mapping process is far from trivial. Fortunately, during the last decade it has been demonstrated that HHG offers a unique opportunity to provide high-frequency structured ultrafast pulses through such up-conversion mechanism.

In this contribution we will review the recent advances in the generation of structured coherent EUV/soft x-ray pulses through HHG. In particular, the use of structured driving beams with controlled SAM or OAM has opened exciting opportunities to harness the properties of the high-order harmonics in an unprecedented way [3].

One of the most appealing advances of HHG is the generation of high-order harmonics and attosecond pulses with controlled polarization—from linear to circular—due to their potential application in the study of chiral media and magnetic materials. Among a wide variety of different techniques [4], non-collinear HHG has allowed the generation of circularly polarized isolated attosecond pulses [5], which has also enabled to access the most fundamental dynamics of HHG through ellipsometry [6].

On the other hand, the use of driving field configurations with custom OAM is opening novel control opportunities over the properties of the high-order harmonics. The generation of attosecond vortices with controlled polarization [7]; high harmonic pulses with time-dependent OAM or self-torque [8]; attosecond pulse trains with time-ordered polarization states [9]; or low-divergence harmonic combs with controlled frequency line spacing extending into the soft x-rays [10], represent some of the most exciting advances. In addition, the perspective of the application of such structured schemes to HHG driven in solid systems [11], is opening very interesting avenues for the study of ultrafast electronic dynamics.

Achieving complete control over the generation of coherent ultrafast x-ray sources with custom angular momentum properties is nowadays possible thanks to HHG. It represents a significant advance towards the quest of capturing the fastest electronic and spin dynamics in a wide variety of materials.

Figure 1: Representation scheme of an ultrafast pulse with self torque (dℓ/dt), carrying a subfemtosecond variation of its topological charge (ℓ) through the high-frequency EUV laser pulse [8].
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References


Towards Spiral-Like Cold Atom States

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Laguerre-Gaussian (LG) beams are the most prominent member of a large family of coherent laser beams known as optical vortices. The photons of such beams are endowed with a quantized orbital angular momentum given by $\ell \hbar$ where $\ell$ is a non-zero integer number known as the winding number of the beam. The transverse intensity pattern of these beams has a characteristic cylindrical symmetry with a zero on-axis intensity and a number of $p+1$ bright concentric regions where $p$ is the so-called radial index of the beam [1]. The optical vortex beams have given a boost to the study of mechanical effects of light [2].

When two similar counter-propagating LG beams, with opposite winding numbers (i.e. $\ell_1 = -\ell_2 = \ell$) interfere the result is a light field with helical bright tubes known as Helical Optical Tubes (HOT). The last years there is an increasing interest in the study of atom trapping in such a field. There are proposals for utilization of this light field in quantum metrology and rotational sensing [3], [4] and for the creation of an Archimedes’ spiral for elevating atoms [5], [6]. Recently an experiment showed that a similar mechanism created by Bessel beams can serve as an Archimedes’ spiral for nano-particles [7].

In our work we study, for the first time, the quantized motion of a very cold atom trapped in a HOT. Our results suggest that when a cold atom relaxes at the ground state of a HOT its wavefunction assumes a twisted spiral-like spatial structure, reflecting to some extent the geometry of the confining potential, while for the excited states we obtain even more exotic spatial probability distributions which, however, retain the main features of the geometry of the confining potential. We contemplate the application of our results in the generation of atom laser beams with twisted spatial structure.


Figure 1. The optical dipole potential for a HOT with $\ell_1 = -\ell_2 = 1$

Figure 2. 3D plots of the atomic position probability distribution of a Rb atom trapped at: (a) the ground state (0,0,0) and (b), (c), (d) at the excited states (0,0,1), (0,1,0) and (0,0,3) respectively. The values of the parameters used are: a total power $P = 5$ mWatt, a detuning $\Delta = -100 \times 10^{13}$ Hz, a beam waist $w_0 = 4 \mu m$, and $\ell_1 = 1$. 
Metasurface for information processing
Anticounterfeiting visible metaholograms multiplexed with spin, direction and wavelength

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Computer-generated holography (CHG) involves iterative numerical algorithms to obtain the phase and/or amplitude profiles needed to physically realize holograms. Metasurfaces consist of arrays of subwavelength nanoresonators that can control the wavefront of light in a desired way. They recently proved themselves to be an effective platform for CGH by surpassing the quality of traditional holograms in terms of image resolution and field-of-view. These metasurface holograms showed prospects not only in imaging and display but also in security applications [1]. In particular, applying metaholograms to anticounterfeiting applications requires not only the technology of encoding multiple pieces of information, but also the manufacturability of highly efficient devices. To meet these complex needs, we have implemented a highly efficient metahologram based on hydrogenated amorphous silicon (a-Si:H) [2].

In this abstract, I will discuss our efforts in realizing multifunctional a-Si:H metaholograms that can encode multiple pieces of information in a monolayer device for anticounterfeiting applications. First, I will present a spin-multiplexed visible metahologram [3]. A straightforward method for encoding multiple pieces of information in a single metahologram device is using polarization. To obtain significant birefringence for the control and reversal of photon spin, two sets of nanorods are designed, and depending on their orientation, they imprint inversed spin photons along their corresponding geometrical phase. As a result, this allows switching between two different images by simply flipping the handedness of the circularly polarized light on the transmission-type metahologram with 61% diffraction efficiency. Second, I will introduce a direction-multiplexed visible metahologram [4]. This approach is to multiplex two distinct pieces of information onto a monolayer metahologram operating in the forward and backward directions depending on the direction of light incident on the device. Particularly, in this part we will reveal underlying physics of high transmission efficiency (around 75%), which is the antiferromagnetic resonances in the a-Si:H nanorod. Finally, I will propose a wavelength-switchable metahologram operating at visible and invisible domain [5]. The device consists of a-Si:H and gold (Au) metasurfaces in a monolayer device, which is fabricated by the electron beam lithography overlay process. The a-Si:H metasurfaces generate a visible hologram and the Au metasurfaces produce a NIR hologram simultaneously with low crosstalk. I believe our efforts for making a multiplexed metahologram will lead to pragmatic anticounterfeiting applications.

[4] I. Kim et al., Nanoscale Horizons 5, 57-64 (2020) [Cover paper]
3D-printed complex-amplitude metasurface for orbital angular momentum holography

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Abstract
Metasurface holograms, consisting of subwavelength structures on a flat surface for optical wavefront shaping, promise new applications in high-capacity information technologies. To increase the bandwidth of a metasurface hologram, different degrees of freedom of light and in particular, orbital angular momentum with an infinite quantum number hold great promise. However, phase-only orbital angular momentum-multiplexing holograms with neglected amplitude information suffer strong crosstalk. Here, we demonstrate the design and 3D laser printing of a large-scale complex-amplitude metasurface hologram for high-dimensional orbital angular momentum-multiplexing holography.

1. Introduction
Recent advances in nanotechnology open the possibility of using ultrathin metasurfaces for complete manipulation of light at interfaces. For improving the bandwidth of a metasurface hologram, optical multiplexing has been largely exploited to use physical properties of light for carrying independent holographic image channels. Orbital angular momentum (OAM), manifested by a twisted wavefront of light, has been recognized as a new degree of freedom of light to significantly boost information capacity [1-5]. However, without careful design, a digital hologram typically destroys the OAM of light in the holographic reconstruction process. Until recently, we have demonstrated the concept of metasurface OAM holography by discovering OAM sensitivity in the spatial-frequency domain [6, 7], which promises future high-capacity holography. However, previous phase-only holograms used for OAM-multiplexing holography prohibit an exact convolution of a complex-amplitude image channel and an OAM helical wavefront, suffering from strong crosstalk. More severely, nanofabrication of a metasurface hologram with a small size of around 200 micrometers by 200 micrometers typically requires a complicated and high-cost fabrication process and limits the holographic reconstruction to a bulky imaging system.

2. Results
Here, we demonstrate the design and 3D laser printing of a large-scale complex-amplitude metasurface hologram for OAM-multiplexing holography. To realize a complex-amplitude Fourier hologram, we have developed an OAM diffuser array with a random phase function capable of scaling down the amplitude variation of the hologram as well as eliminating the coherence of holographic image channels. As a result, OAM beams with continuous helical mode indices ranging from -50 to 50 have been incident on the complex-amplitude hologram to address a wide range of OAM-dependent orthogonal image frames. In addition, we present a novel design and laser printing of a large-scale (in a size of 2.5 mm by 2.5 mm) metasurface hologram through exploiting 3D design degrees of freedom of a polymer-based meta-atom, offering independent and complete manipulation of both amplitude and phase responses of transmitted light.

3. Discussion
Our demonstrated orbital angular momentum-multiplexing holography provides a holographic paradigm shift for future realistic holographic 3D video display and wearable devices for augmented reality. In the meantime, we have demonstrated the capability of 3D laser printing of a large-scale complex-amplitude metasurface, unlocking the full degrees of freedom of a metasurface. Such 3D-printed metasurfaces may inspire novel metasurface design for a wide range of photonic applications in which current flat
optics has marked significant impacts. Therefore, we envision our demonstration integrating the novel design of an ultrahigh-bandwidth multiplexing hologram with a large-scale 3D-printed metasurface has broad impacts on future wearable displays, ultra-secure optical encryption, high-capacity data storage, deep-learning microscopy, advanced optical trapping, and artificial intelligence.

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References


Optical Metasurface for Engineered Polarization Profile

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Abstract
The unprecedented capability of optical metasurfaces in the manipulation of the light’s polarization at sub-wavelength resolution has provided an unusual approach for arbitrary manipulation of polarization profiles. A compact metasurface platform has been demonstrated to arbitrarily engineer a polarization profile that is very difficult or impossible to realize with conventional optical elements. We have developed various metasurfaces to engineer the polarization profile of a light beam.

1. Introduction

Like amplitude, phase and frequency, polarization is one of fundamental properties of light. A laser beam usually has a homogeneous polarization after passing through a polarizer, while a vector beam has an inhomogeneous distribution of polarization in the transverse plane perpendicular to propagation. Vector beams have been recognized as a promising future technology in quantum memories, particle trapping, and high-resolution lithography. However, the real-life applications remain limited, mainly because of complexity of the experimental system and the inability to arbitrarily manipulate polarization state of light at subwavelength scale. Many devices such as liquid-crystal q-plates have been proposed to generate vector beams such as widely explored radially and azimuthally polarized beams. However, these devices could not be straightforwardly downsized, preventing widespread applications in integrated optics. Furthermore, the limitations of poor resolution and low damage threshold still need to be overcome for practical applications. There are numerous challenges, either fundamental or technological, in building devices that are compact, efficient, and integrable [1]. In this talk, we are going to talk our recent work on arbitrary polarization manipulation based on metasurfaces. Examples include image concealment [2-4], multichannel metadevice for anti-counterfeiting and encryption [5], nonlinear vectorial metasurface for optical encryption [6], and multi-foci metalens with polarization rotation capability [7].

2. Results

The structured beam that used to hide an image is created by a metasurface illuminated by the laser light at normal incidence. A linear polarizer is used to seek the hidden image in the generated structured beam. According to Malus’ Law, when completely plane polarized light is incident on the analyzer, the intensity of the light transmitted by the analyzer is directly proportional to the square of the cosine of angle between the transmission axes of the analyzer and the polarizer.

Figure 1: (a) Schematic for hiding a high-resolution grayscale image [1]. (b) Generation of QR code for anti-counterfeiting [2]. (c) Top: Schematic for the polarization encoded colour image. Bottom: Experimental results for incident light with red, green and two colors [3]. (d) Schematic of the multichannel metadevice for anti-counterfeiting and encryption [4]. (e) Schematic of nonlinear vectorial metasurface for optical encryption [5].

The generated structured light in Fig. 1a has a very specific polarization in the light beam, thus the electromagnetic field oscillates differently for different parts of the beam. In order to visualize the hidden image in the polarization topology of the laser beam, we reveal the grayscale of the image by using an analyzer (linear polarizer). In doing so, we do not directly observe the spatially-variant polarization profile of the laser beam but rather indirectly confirm its existence through the intensity profile (grayscale image) behind the analyzer. Because the theoretical amplitude of the two beams are exactly the same, no image is observed in the beam without the aid of the analyzer. The experimental result indicates that the image-hidden functionality is unambiguously realized. Similarly, a QR code can also be hidden in the polarization profile of a light beam (Fig. 1b). We also demonstrate a metasurface platform for simultaneously encoding color and intensity information into the wavelength-dependent polarization profile of a light beam (Fig. 1c). This unique approach features the combination of wavelength selectivity and arbitrary polarization control down to a single subwavelength pixel.
level. Upon the illumination of a linearly polarized light beam with multiple wavelengths, a color image is revealed after the light beam passes through a dielectric metasurface and a linear optical polarizer.

A multichannel metasurface device is developed to realize an image-switchable hologram and arbitrary polarization manipulation for a hidden image (Fig. 1d). A dielectric metasurface consisting of nanopillars with spatially variant orientations is used to realize distinct functionalities in multiple channels. The two holographic images can be switched by changing the helicity of the incident light, while the encoded image in the polarization profile of the light beam can be revealed by a polarizer. The unprecedented capability of metasurface in manipulation of light propagation has been extended to the nonlinear optical regime. A nonlinear photonic metasurface is experimentally demonstrated to generate a vectorial polarization profile for nonlinear imaging (Fig. 1e).

Figure 2 shows the schematic for multi-foci metalens with polarization-rotated focal points. The polarization axis of the incident linearly polarized light beam is rotated at each focal point. The simplicity and robustness of our design not only provide a platform for simultaneous multiplexing of focusing and polarization rotation, but also open a novel avenue for polarization-dependent imaging.

![Figure 2: Multi-foci metalens with polarization-rotated focal points [7].](image)

3. Discussion

The obtained image shows how the electric field is oriented in the beam profile of the laser beam. These hidden images demonstrate the rich polarization structure that a light beam can possess at subwavelength scales. The precise control over the polarization state of light is faithfully mapped onto the intensity profile for each color. Polarization related ultrathin nanodevices, nanophotonic systems, and integration of multifunctional capability into ever smaller and more flexibly connected and deployable units will be an immensely important re-search topic in the years ahead.

4. Conclusions

Metasurface enabled arbitrary polarization manipulation is a new research field. The precise control over the polarization state of light can be faithfully mapped onto the intensity profile for each color. Polarization related ultrathin nanodevices, nanophotonic systems, and integration of multifunctional capability into ever smaller and more flexibly connected and deployable units will be an immensely important re-search topic in the years ahead.

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References

Terahertz Active Metasurface

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Abstract
Metasurface provides a number of approaches to manipulate the wavefront of light. Active control of the metasurface will bring more fascinating applications. We introduce two terahertz active metasurface devices which are fabricated with vanadium dioxide. With thermal exciting, the functions of devices can be switched on and off. The performances of the devices are characterized with a focal plane terahertz imaging system. It was found that the fabricated devices can achieve the preset functions well.

1. Introduction
Terahertz radiation, which is located between the infrared and microwave in the electromagnetic spectrum, has many potential applications in biological spectroscopy, nondestructive inspection, as well as wireless communication [1]. However, comparing with the fast development of terahertz sources and detectors, the functional terahertz devices, especially the dynamic tunable functional devices, are still in great demand. Metasurface, a kind of artificial materials, can modulate the amplitude, phase, and polarization of electromagnetic wave and provides a number of approaches to manipulate the wavefront of light. Furthermore, the performance of these metasurface devices can be tuned by applying an external voltage, optical pumping, or mechanical force.
Vanadium dioxide (VO₂) is a kind of transition metal oxide [2], it can undergo an insulator-to-metal transition at the temperature higher than 68 degree. Several works have been reported to fabricate active terahertz devices by combining the VO₂ thin films and metamaterials. In this presentation, we will introduce two works on thermally switchable terahertz metasurfaces. The function of the device can be turned on or turned off by increase the environment temperature. The characteristics of devices have been investigated in the frequency range of 0.2 to 1.2 THz with a terahertz focal plane imaging system. Experimental results demonstrate that the fabricate devices can achieve the preset functions well.

2. Experimental results
The first device is a tri-layer structure consisting of a gold metasurface fabricated in a 200 nm thick gold film, a VO₂ film, and a quartz substrate [3]. The metasurface consists of 40*40 units. Each unit contains a V-shaped slot antenna. The size of the device is 10*10 mm². The metasurface is designed as a lens with a focal length of 3 mm. A terahertz focal plane imaging system is employed to measure the phase and amplitude distributions of terahertz wave on the focal plane of lens. The measured results are shown in Fig. 1. When the environment temperature is 20 degree, the device is working in its ‘on’ state, a bright focal point appears in the middle of the focal plane, as shown in Fig. 1(a). The focal spot size is about 400 μm. When the temperature is increased to 80 degree, the measured amplitude distribution on the focal plane is shown in Fig. 2(b), the focal point disappears. When the environment temperature is lower than the critical temperature (about 67 degree for VO₂), the VO₂ film is in its insulating state and is transparent for the terahertz wave, thus the metasurface can focus the terahertz wave into a point. When the environment temperature is higher than the critical temperature, the VO₂ film is translated to the metal state. The metalized VO₂ film will block the transmission of the terahertz wave, therefore, no terahertz field can be found on the focal plane, thus the device works in its ‘off’ state. The amplitude of terahertz decreases from 0.14 to 0.04 when the temperature is changed from 20 degree to 80 degree. The modulation depth can reach 91.8 %. The corresponding phase distributions are shown in Fig. 1(c) and (d), respectively, which confirmed the above analysis.

The tri-layer device works in its ‘on’ state when the temperature is lower than the critical temperature and its function will be turned off when the temperature is higher than the critical temperature. However, for some applications, the function of the device is required to be turned on when the temperature is higher than the critical temperature. In order to satisfy this requirement, we fabricated a whole VO₂ metasurface. The device consists two layers, a 330 μm VO₂ thick film and a quartz substrate. The metasurface structure is etched in the VO₂ film and its function is a multi-focus lens [4, 5]. The experiment results are shown in Fig. 2. When the temperature is 20 degree, the amplitude distribution of the terahertz wave on the focal plane is given in Fig. 2(a). It is a uniform distribution which means that the terahertz wave can pass through the device. Since the VO₂ is in its insulating phase, the function of the device is switched off. When the temperature is increased to 70 degree, which is higher than the critical temperature, the VO₂ film will work in its metallic
phase, thus microstructure in the film will affect the transmitted terahertz radiation, four focal points are generated on the focal plane, as shown in Fig. 2(b). In this case, the function of the device is turned on. The experimental results show that the phase transition has not been affected by the micro structuring of the film and the antenna structures can indeed serve as active building blocks of terahertz active metasurface.

Figure 1: Experiment results for tri-layer active metasurface. Measured amplitude distributions on the focal plane when the temperature is 20 degree (a) and 80 degree (b), respectively. (c) and (d) are corresponding phase distributions.

Figure 2: Switching characteristics of the VO$_2$ metasurface. Amplitude distributions on the focal plane when the temperature is 20 degree (a) and 70 degree (b).

3. Conclusions

Two kind of thermally switchable terahertz metasurface devices based on the phase transition of VO$_2$ are demonstrated. The dynamic control of the terahertz is feasible for both two devices. This kind of thermally switchable terahertz metasurface devices with a capability of dynamically steering terahertz fields will be of great significance for the future development of terahertz active devices.

Acknowledgements

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References


We propose to combine coherent and wavefront control with metasurfaces to carry out designer unitary transformations. The developed framework will be useful for carrying out mathematical operations and quantum information processing.

1. Introduction
Metasurfaces have been proved to be a very versatile platform to provide very complex light matter interaction. The huge amount of degrees of freedom embedded in the metasurfaces, in many cases in a form of nanostructures with anisotropic response, can be used to control wavefront from simple steering to generating high-resolution holograms [1,2]. On the other hand, the degree of freedom of the incident light can be used as a coherent control of the metasurfaces function. For example, for a pair of coherent beams counter-propagating to the metasurfaces can induce constructive and destructive interference and tune the metasurfaces from complete absorption to complete transmission [3,4]. Here, we explore and establish a framework on how coherent control can be used on the metasurfaces to construct designer unitary transformations on the state of the light. Such a framework can be useful to carry out mathematical operations, which can be potentially useful for quantum optical information processing [5].

2. Coherent unitary control framework
First, the setting of the metasurface is described in Figure 1, in which two beams are coherently incident on a metasurface, schematically represented by a box in gray color. The two beams are at 45 degrees incidence on the two sides (forward and backward) of the metasurfaces, which can be at either TE (vertical) or TM (horizontal) polarizations. In terms of a quantum optical representation, the state of the light can be represented as

$$|\psi\rangle = E_{V,1}|0,0\rangle + E_{V,2}|0,1\rangle + E_{H,1}|1,0\rangle + E_{H,2}|1,1\rangle,$$  

where for the computational basis $|i,j\rangle$, the polarization qubit is denoted in the first index with $i = 0$ (1) for vertical (horizontal) polarization, and the path qubit is denoted in the second index with $j = 0$ (1) for the beam 1 (2). The unitary scattering matrix, with the assumption of a lossless dielectric metasurface, relates the state of the incident light to the state of the outgoing light as

$$
\begin{pmatrix}
E_{V,1}^{(\text{out})} \\
E_{V,2}^{(\text{out})} \\
E_{H,1}^{(\text{out})} \\
E_{H,2}^{(\text{out})}
\end{pmatrix} = S
\begin{pmatrix}
E_{V,1}^{(\text{in})} \\
E_{V,2}^{(\text{in})} \\
E_{H,1}^{(\text{in})} \\
E_{H,2}^{(\text{in})}
\end{pmatrix}.
$$

The in/out ports are indicated in Figure 1 as well. In quantum optical operations, it is the same unitary matrix $S$ accounts for single-photon operation and for constructing the higher order unitary operation in the Fock space for multi-photon operations by promoting the field amplitudes to creation and annihilation field operators. Therefore, the ability to construct such a unitary $S$ is in vital importance. Here, we will introduce several designs that can allow us to have a specific control in constructing such unitary $S$ matrix.

![Figure 1: Device concept of metasurfaces in carrying out unitary transformations.](image-url)
3. Metasurfaces with designer unitary transformations

We will investigate several examples of designer metasurfaces in carrying out specific unitary transformations. As an example, we start from metasurfaces to carry out 1 qubit operations. Without losing generality, we focus on metasurfaces with only TE (or vertical) polarization and only employ the path qubit. In this case, it reduces to a 2x2 unitary S matrix (belong to the U(2) operations) and is sufficient for discussion. Figure 2 shows the reflection and transmission amplitudes of a designer structure in a “pit-bulge” shape with a tunable parameter $\theta$ of the geometry. The unit transmittance at one configuration ($\theta$ as 45 degrees) with 180 degrees phase difference in transmission amplitudes between the forward and backward incidence indicates that the operation is a $\sigma_z$-operation while the other configuration ($\theta$ as 90 degrees) with 180 degrees phase difference in the reflection amplitudes indicates that the operation is a $\sigma_y$-operation. More importantly, some other unitary transformations can be obtained for configurations in between the two operations.

![Figure 2: A metasurfaces in realizing $\sigma_z$ to $\sigma_y$-operations when the intersection angle varies from 45 to 90 degrees.](image)

4. Conclusions

We have introduced a framework in constructing arbitrary unitary transformations using metasurfaces. A single qubit operation is used as example. Furthermore, we can extend to two-qubit operations by considering a 4x4 unitary scattering matrix as we introduced. Without going into further details, such a methodology can be used to construct unitary matrices that correspond to two-qubit operations, such as a CNOT gate.

Acknowledgements

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References

Anomalous Brewster Effects and Ultra-broadband Reflectionless Brewster Absorbers Protected by Reciprocity

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Abstract
The Brewster’s law predicts zero reflection of p-polarization on a dielectric surface at a particular angle. However, when loss is introduced into the permittivity of the dielectric, the Brewster condition breaks down and reflection unavoidably appears. Here, we found an exception by creating a class of nonmagnetic anisotropic metamaterials, where anomalous Brewster effects with independently tunable absorption and refraction emerge. Ultra-broadband reflectionless Brewster absorbers with bandwidth covering from dc to optical frequencies, are bestowed by the anomalous Brewster effects.

1. Introduction
In the early 1810’s, Sir David Brewster experimentally showed that when unpolarized light impinges on a dielectric interface, the reflected light would be linearly polarized if the reflected beam is perpendicular to the refracted one [1]. The origin of this Brewster effect lies in the elimination of reflection that occurs for the p-polarized light at the Brewster’s angle. However, when loss is introduced to the permittivity of dielectrics, a phase difference between the electric and magnetic fields appears, which introduces substantial reflection and breaks the Brewster condition [2, 3].

In this work, by designing anisotropic metamaterials, we reveal an anomalous Brewster effect that allows independently tunable absorption and refraction in an ultra-broadband spectrum from dc to optical frequencies [4]. No matter how large the absorption is, zero reflection can be maintained for p-polarization, which is impossible in previous traditional Brewster effects. Such an amazing effect is bestowed by anisotropic metamaterials designed under the guidance of the reciprocity principle. In this metamaterial, the anisotropy introduces extra degrees of freedoms to tune the absorption and refraction without affecting the Brewster condition. Therefore, loss-independent Brewster effect can be realized where the damping can be sufficiently large to achieve almost total absorption within a thickness of 1–2 wavelength.

2. Anomalous Brewster effect

When light is incident from an isotropic dielectric onto the surface of a tilted anisotropic medium, a Brewster angle $\theta_B$ can be obtained, say, for $\theta > 0$. In this situation, the reflection is zero. The transmitted wave cannot “see” the permittivity component along the orthogonal direction of the electric field, say, $\varepsilon_y$ . Therefore, tuning this permittivity component $\varepsilon_y$ will have no influence to the Brewster effect. Interestingly, by applying the reciprocity principle, the reflection should also be zero under the opposite incident angle of $-\theta_B$ (the anomalous Brewster angle). However, under this angle, the transmitted wave can now “see” the permittivity component $\varepsilon_y$. Therefore, by tuning $\varepsilon_y$, both the angle of refraction and the absorption rate can be conveniently controlled, without destroying the Brewster effect, as protected by the reciprocity principle. It is thus denoted as the anomalous Brewster effect.

3. Ultra-broadband Reflectionless Brewster Absorber

Based on this anomalous Brewster effect, ultra-broadband and high-efficiency Brewster absorbers can realized. Such Brewster absorbers can be constructed as tilted arrays of conductive films. At the Brewster angle, the Brewster absorber has neither reflection nor absorption. While at the anomalous Brewster angle, the reflection is also zero, but the absorption can be huge. The hallmark advantage of such Brewster absorbers is that they can possess ultra-wide...
working bandwidth, potentially from dc to optical frequencies. At the optimal condition, 90% of the incident wave energy can be absorbed within a thickness of 1-2 wavelength. Since the Brewster absorbers have no reflection, perfect absorption can be achieved for electromagnetic waves of any frequency as long as the sample is thick enough.

Figure 2: Experimental verification of the Brewster absorbers. (a) The sample of Brewster absorber constructed by tilted array of conductive films. The (b) reflectance, (c) absorbance as functions of the incident angle and frequency.

4. Conclusions

In summary, in this work, we reveal an anomalous Brewster effect for ultra-broadband reflectionless manipulation of waves, including tunable absorption and refraction. The anomalous Brewster effect, as protected by the reciprocity principle, guarantees zero reflection for one polarization at a particular incident angle. At the same time, the refraction and absorption are flexibly tunable via the extra degrees of freedoms introduced by the anisotropy of metamaterials. The anomalous Brewster effect bestows reflectionless Brewster absorbers with an unprecedented wide bandwidth of impedance-matched absorption. While conventional wisdom tells us that addition of loss will destroy the Brewster effect, we have demonstrated that the mechanism of reciprocity protection escapes from such a deficiency.

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References


Parity-Time and quasi-normal modes in Photonics, Plasmonics, Acoustics
Nonorthogonality constraints in open quantum systems

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Abstract

The nonorthogonality of quasi-normal modes plays an important role in the physics of non-Hermitian systems. We demonstrate that the known nonorthogonality bound for effective Hamiltonians describing decaying systems may not be valid in quantum and wave systems with radiation due to quantum backflow. A geometric interpretation of the nonorthogonality bound is given which reveals that in this context the complex energy (or frequency) space can be seen as a surface of constant negative curvature.

1. Introduction

In the emerging fields of non-Hermitian physics and parity-time symmetry it became clear that nonorthogonality of energy eigenstates (quasi-normal modes, modes henceforth) is not just an inconvenience but signals interesting physics. For instance, nonorthogonality can lead to nonexponential transient decay [1], power oscillations in optical waveguides [2], chirality in perturbed whispering-gallery microcavities [3], sensitivity of resonance widths under perturbation [4], limitation of mode selectivity [5], and quantum excess noise in lasers [6].

It has been known since the fifties that in decaying quantum systems there is an upper bound for the squared modulus of the overlap of two normalized modes $|\psi_i\rangle$ and $|\psi_j\rangle$ [7]

$$|(\psi_i|\psi_j)|^2 \leq \frac{\gamma_i\gamma_j}{\Delta^2 + (\gamma_i + \gamma_j)^2/4},$$

with the conventional scalar product $\langle \cdot | \cdot \rangle$, the energy (or frequency) detuning $\Delta_{ij} = Re E_i - Re E_j$, and the individual decay rates $\gamma_j = -2 Im E_j \geq 0$. One known interpretation of the inequality (1) is that the right-hand side can be understood as spectral overlap of the two modes in terms of their associated normalized Breit-Wigner (Lorentz) distributions [8], as illustrated in Fig. 1.

In this contribution, we present several new results [9] related to the inequality (1). For example, we prove the inequality for monotonously decaying systems with effective Hamiltonian in a transparent way using the concept of Hermitian forms, and we demonstrate that the inequality becomes an equality for a single-channel decay.

2. Wave systems with radiation

The situation is more involved for systems described not by an effective Hamiltonian but by a wave equation subjected to outgoing-wave conditions. Even though individual modes radiate and therefore decay monotonously, this is not true for general wave functions due to quantum backflow [10, 11] (also called optical backflow in optics [12]). This remarkable effect can be illustrated with a one-dimensional example of a free particle with wave function being a coherent superposition of two plane waves

$$\psi(x) = e^{ik_j x} + \alpha e^{ik_l x}$$

where we assume $k_l, k_j, \alpha \in \mathbb{R}$. A simple calculation gives for the current

$$j_x = \frac{\hbar}{m} \left\{ k_j + \alpha^2 k_l + \alpha (k_j + k_l) \cos [(k_j - k_l)z] \right\}.$$
Due to the third term the current can be negative for certain intervals in space even if both wave numbers \( k_l \) and \( k_j \) are positive, see the example in Fig. 2.

The quantum backflow renders the decay to be non-monotonous. Thus the assumption on which the proof of inequality (1) is based is not true for wave systems with radiation. An example where the inequality is not valid is given. Note that the lack of an upper bound for the overlap can be seen as an advantage as it allows for larger non-Hermitian effects.

### 3. Geometric interpretation

We reveal that the inequality (1) can be written as a relation between distances in Hilbert space and complex energy space as

\[
d_{\text{HS}}(\psi_l, \psi_j) \geq d_{\text{ph}}(E_l, E_j)
\]

with the Hilbert-Schmidt distance

\[
d_{\text{HS}}(\psi, \psi) = \sqrt{1 - |\langle \psi | \psi \rangle|^2}
\]

and the pseudo-hyperbolic distance on the lower half complex plane

\[
d_{\text{ph}}(E, E') = \frac{|E - E'|}{|E^* - E'|}.
\]

Hyperbolic distances describe surfaces of constant negative curvature.

The inequality (4) states that modes that are “spectrally close” – now rigorously defined by the distance function \( d_{\text{ph}} \) in Eq. (6) – can be also close in Hilbert space measured by the distance function \( d_{\text{HS}} \) in Eq. (5), i.e., strongly nonorthogonal.

### References


Observation of exceptional arcs and cusp singularities in acoustics

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Abstract

The known fact that two singularities can be connected by geometric arcs reveals fundamental excitations of materials, such as Fermi arc and the associated interface modes. Such concepts have been generalized to non-Hermitian scenarios recently. For example, two order-2 exceptional points (EPs) are connected by the non-Hermitian Fermi arc. However, it is still an open question that which geometric structure connects two higher-order EPs. Here we demonstrate both theoretically and experimentally that it is the exceptional arc that bridges two order-3 EPs and produces the cusp singularity at the order-3 EP. The studied system is a three-state non-Hermitian system which has been realized by the ternary acoustic cavity system with dissipative losses. We show that an order-3 EP holds a fractional topological charge of 2/3. The exceptional arcs and the cusp singularity are observed in acoustic experiments. In addition, our study reveals surprising critical behaviors for both the eigenvalues and eigenvectors in the vicinity of the order-3 EP when it is approached from different directions. Our findings enrich the fundamental understanding of multi-state non-Hermitian systems and may open new opportunities for applications exploring non-Hermiticity.

1. Introduction

The advent of non-Hermitian physics in optics and classical waves, such as parity-time (PT) symmetric systems, greatly expanded the horizon of their manipulation, giving rise to a myriad of novel phenomena. Perhaps the most fascinating signature of non-Hermitian systems is the existence of EPs, specific parametric points at which two or more eigenstates coalesce. An EP is a branch-point singularity in the parameter space that carries a non-zero topological charge. Recently, the smart engineering of the parameter space has led to a myriad of exotic EP structures, such as the ring of EPs, EP surfaces, or anisotropic EPs. It has been shown that a Dirac cone in photonic crystals can spawn two separate order-2 EPs (EP2), each possessing a 1/2 topological charge of opposite sign. These two EPs are joined by a bulk Fermi arc, i.e., a two-fold nodal curve of bulk states on which the real parts of two eigenvalues are degenerate. However, it is worthy studying the geometric structure which connects the higher-order EPs.

2. Results

In this work, we show that nodal arcs entirely consist of order-2 EPs, which we call “exceptional arcs,” can arise a three-state non-Hermitian system in a parameter space spanned by synthetic dimensions. Totally four exceptional arcs exist as two time-reversal pairs. The two arcs belonging to the same pair are pinned at a specific point in the parameter space and are open in the Hermitian limit for finite system parameters, and they. Interestingly, this “exceptional cusp” is also an anisotropic order-3 EP that possess a fractional topological charge of 2/3. We performed acoustic experiments to observe the exceptional arcs and order-3 EP. Moreover, we conducted thorough theoretical and experimental investigations on both the eigenvalues and the eigenvectors of the system to fully reveal all the nearby singular behaviors, including the anisotropic characteristics of the order-3 EP.

Figure 1: (a) A ternary acoustic cavity system that realizes the three-state non-Hermitian Hamiltonian. (b) Projection of the exceptional arcs on the δg-δε₃ plane. The two arcs meet at the order-3 EP and give rise to a cusp singularity.
3. Discussion and Conclusions

In summary, we show that it is the exceptional arc that bridges higher-order EPs and produces the associated cusp singularity. Our study also reveals that a higher-order EP can possess rich singular behaviors that far exceed previous expectations, namely the critical exponents of eigenvalues and eigenfunction when we approach the order-3 EP from different parameter direction. On a fundamental level, these anomalous behaviors imply an EP’s order cannot be reliably determined solely by the singularity of the eigenvalues. From a practical point of view, leveraging on these rich behaviors unique to higher-order EPs may open new avenues for applications, such as sensors simultaneously monitoring different parameters, lasers with different thresholds, multiplexing of waveguiding channels, etc.

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References

A universal form of one-dimensional complex potentials featuring spectral singularities

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Abstract

A one-dimensional complex potential in the Schrödinger equation features spectral singularities if and only if it has a universal form. Respective solutions have a universal form too. This allows one to construct complex potentials enabling either coherent perfect absorption or to lasing, or to both, at any prescribed wavelength. The described potentials allow for deformations leading to bound states in continuum or to exceptional points. We also describe potentials resulting in two or in three spectral singularities at desirable wavelengths.

1. Introduction

It is known that such phenomena as coherent perfect absorption (CPA) and lasing are related to the spectral singularities (SS) of spectra of non-Hermitian operators with complex potentials. Therefore obtaining potentials resulting in SSs at apriori given wavelengths is a relevant practical problem. This issue was addressed in a number of previous studies (see e.g. [1, 2, 3]), where it was shown how to construct potentials yielding prescribed SSs, although for the potentials defined on a finite spatial domain. In this work we show that potentials defined on the real axis and featuring SSs, all have a universal form, as well as the respective solutions. Having established this fact one can describe a method of designing potentials with SSs at apriori given wavelength [4]. The method is generalized to the case when the number of required SSs is two or three.

2. The model

We consider a one-dimensional Schrödinger equation

$$-\psi'' + U(x)\psi = k^2 \psi,$$

where $U(x)$ is a spatially localized complex-valued potential, i.e.

$$\lim_{x \to \pm \infty} U(x) = 0,$$

and $k$ is a spectral parameter (hereafter a prime stands for a derivative with respect to $x$).

We are interested in solutions $\psi_0(x)$ of (1) which are a continuously differentiable, i.e., $\psi_0 \in C^1(\mathbb{R})$, and for a given value of the spectral parameter $k = k_0 \in \mathbb{R}$, are characterized by the asymptotics

$$\lim_{x \to \pm \infty} [\psi_0^{(n)}(x) - (\pm i k_0)^n e^{\pm ik_0 x} \rho_{\pm}] = 0, \quad \rho_{\pm} \neq 0 \quad (3)$$

where $n = 0, 1, 2$ [the superscript “(n)” denotes the $n$th derivative in $x$] and $\rho_{\pm} \in \mathbb{C}$ are nonzero complex constants. Such solutions are referred to as a SS-solution, while $k_0$ is referred to as a SS. An SS-solution $\psi_0(x)$ describes lasing for $k_0 > 0$ and CPA for $k_0 < 0$.

3. Main results

We formulate the solution of above problem in a form of necessary and sufficient conditions for a Schrödinger operator to have a SS. Dropping mathematical subtleties, these two statements can be formulated as follows.

The necessary condition [4] defines that if a function $\psi_0(x)$ with the asymptotic (3) is a solution of Eq. (1), then the potential $U(x)$ necessarily has the representations as follows

$$U(x) = -w^2(x) - i w'(x) + k_0^2, \quad (4)$$

where the complex-valued base function $w(x)$ has the asymptotics as follows

$$\lim_{x \to \pm \infty} w(x) = \mp k_0, \quad \lim_{x \to \pm \infty} w'(x) = 0. \quad (5)$$

For $k_0 = 0$ and real-valued function $w(x)$, the potentials of the type (4) were introduced in earlier works [5, 6].

The solution corresponding to the SS of (4) reads

$$\psi_0(x) = \rho \exp \left[-i \int_{x_0}^{x} w(\xi) d\xi \right], \quad (6)$$

where $x_0$ and $\rho$ are arbitrary constants ($\rho \neq 0$).

Loosely speaking, the sufficient condition [4] establishes, that for the existence of a SS solution (that must have the form (6)) it is sufficient for the complex potentials of Eq. (1) to have the form (4). We emphasize that the potential $U(x)$ is not required to be differentiable, and thus both necessary and sufficient conditions are applicable for the potentials on finite supports, studied earlier [1, 2, 3].
3.1. Bound states in continuum and exceptional points

Having a solution in the general form (6) and allowing for $k_0$ to be in the upper complex half-plane (i.e., $\text{Im} k_0 > 0$), one can construct complex potentials with solutions having the asymptotics

$$\lim_{x \to \infty} \psi_0(x) = \lim_{x \to -\infty} \psi_0(x) = 0.$$ \hspace{1cm} (7)

These solutions can be summarized as follows:

• A bound state with the real part $k_0^2$ outside of continuum if

  $$\arg k_0 \in (\pi/4, 3\pi/4) \quad \text{and} \quad \int_{-\infty}^{\infty} \psi_0^2 dx \neq 0.$$ 

  Such bound states can be:

  – stationary, if $\text{Re} k_0 = 0$,
  – growing if $\text{Re} k_0 > 0$,
  – decaying if $\text{Re} k_0 < 0$.

• A bound state with the real part in continuum (quasi-BIC) if $\arg k_0 \in (0, \pi/4) \cup (3\pi/4, \pi)$.

• Exceptional point (EP) if $\int_{-\infty}^{\infty} \psi_0^2 dx = 0$. Depending on the $\text{Re} k_0$ an EP-solution can be stationary, growing or decaying.

4. Generalizations

Based on the explicit representation (6) we also show how it is possible to construct potentials having two different and three different SSs. In the case of special symmetries of the base function $w(x)$ construction of potentials featuring self-dual SS is possible. While the procedure can be formally continued for higher number of SSs, it apparently becomes unsolvable. All types of the solutions listed above are illustrated on explicit examples.

5. Conclusions

We have proven that complex potentials of one-dimensional Schrödinger equations resulting in spectral singularities of the spectra have a universal form, as well as the respective solutions. This fact allows one to formulate an algorithm of constructing complex potentials with prescribed one, two or three different spectral singularities.

Acknowledgement

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References

Spectral singularities and non-reciprocal light scattering in 2D PT-symmetric metamaterials

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Abstract

We consider vertically stacked GaInP PT-symmetric resonators that constitute meta-atoms for the 2D active metamaterial. From numerical simulations and scattering theory formalism, we show that these metasurfaces support zero-width resonances, i.e. spectral singularities (SS). By tuning the coupling between gain and loss resonators, we demonstrate the spectral singularities are robust over a wide range of parameter variations. We also show that vertically stacked GaInP resonators can exhibit broadband unidirectional invisibility and strong directional scattering.

1. Introduction

The existence of real spectra in the non-Hermitian systems exhibiting PT (parity-time-reversal) symmetry inspired the exploration of counter-intuitive dynamics like single-mode lasing and unidirectional invisibility[1]. These novel phenomena are closely associated with the notion of ‘Exceptional points’[2] (EPs) – a class of branch point singularities wherein the non-Hermitian system transits from the PT-symmetric phase (real eigenvalues) to PT-broken phase (complex eigenvalues). Beside EPs there exists another class of spectral points called ‘Spectral singularities’[3] that corresponds to discontinuities in a complete spectrum where the scattering coefficients tend to infinity. Unlike EPs, these spectral singularities can occur only in the presence of gain. Being poles of a scattering matrix at real frequencies SS manifest as zero-width resonances. These extremely narrow linewidth resonances find potential use in applications where strongly localized fields are desired like super scattering, and CPA-laser[4].

Most of the reported works in the context of EPs and SS have used micron-scale photonic structures because accomplishing gain in nano structures is difficult. In this work, we propose an active 2D metamaterial design, operating at optical wavelengths, that realizes the presence of a robust SS tuned through coupling between PT resonators. The structure shows broadband unidirectional invisibility and strong directional far-field scattering.

2. Simulation Details

As depicted in Fig. 1, we consider two-dimensional metasurface comprising of a PT-symmetric, vertically coupled GaInP cylinders on a glass substrate. The coupling is determined by the thickness $g$ of the SiO$_2$ spacer layer, and the structure is embedded in SiO$_2$ for a symmetric environment. The physical dimensions of individual resonator and lattice periodicities are tuned to overlap the resonance of the structure with the gain spectrum of GaInP. As shown in Fig. 1(b), the index profile for gain and loss resonators satisfies the condition of PT-symmetry. To mimic realistic case, wavelength-dependent dispersion is considered with TM polarized light, i.e., E-field oriented along $x$-axis. This geometry shows longitudinal modulation of gain-loss cylinders for the incident wave-vector $k$. The structure is studied numerically with 3D full wave simulation using commercial FEM software, COMSOL™.

3. Results and Discussion

Spectral singularities are the real poles of a scattering matrix, wherein for given finite input power, the output becomes unbounded. This condition corresponds to the lasing threshold in the classical laser physics, evidently showing SS can occur only in the systems having a net gain. Figure 2(a-d) illustrates how the spectral singularities evolves as the PT-dynamics change with the gap between the resonators for light incident from the loss or gain side. For smaller gaps, when the structure is in PT-symmetric phase, i.e., balanced gain-loss, no spectral singularities are present. In the PT-broken phase, SS appears and becomes stronger with the net gain in the system. Figure 2(b) shows...
the clear signature of SS at \( \lambda = 640 \) nm and \( g = 108 \) nm, where both the transmission and reflection becomes unbounded. From Fig. 2(a), (c), and (d) the continuous presence of SS over the range of varying gap while shifting to another wavelength is clearly visible. With the increasing gap and side-by-side coupling of the modes in loss and gain resonators, a red-shifting trend is observed. Unlike previously reported spectral singularities, the proposed vertically coupled resonators show robust SS over a wide range of gap parameter, which also allows us to tune them. Although the transmission is reciprocal, the reflection is non-reciprocal due to asymmetric environment seen when light is incident from opposite sides. Figure 2(d) shows the regions of broad range unidirectional invisibility corresponding to the reflection contrast \( |R_{\text{gain}} - R_{\text{loss}}| / |R_{\text{gain}} + R_{\text{loss}}| < 1 \). In the far-field domain, scattered E-field is directed towards the loss side irrespective of the excitation port, as shown in Fig. 2(f). Also, the magnitude of E-field is much stronger in the case of excitation from the loss side. The electric and magnetic field profiles at \( \lambda = 640 \) nm and \( g = 108 \) nm are plotted in Fig. 2(g). Each gain and loss resonator supports higher-order modes with the gap thickness determining the coupling between them. The study of the interplay of loss and gain resonators, the interference between their modes and the overall 2D-lattice resonances, and scattering cross-sections together with a rigorous eigenvalue analysis in this open scattering system is currently underway.

4. Conclusions

In conclusion, we demonstrate the existence of spectral singularities in an open PT-symmetric nanoresonator scattering system for the visible spectrum. This SS in the proposed structure offers two unique advantages: (i) they are robust to parameter variations and tunable with the wavelength; and (ii) the far-field scattering is highly directional. The enhanced lifetime due to strong localization of the fields at SS and unusual directional response suggest their applications, where strong light-matter interaction with directionality is desired.

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References

Supersymmetric signatures of topological states

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Abstract
By contrasting settings of photonic graphene, topological CROWs, quantum walks, and mesoscopic devices, I clarify the physical consequences of supersymmetry, which is hidden behind the mathematical description of topological effects in chiral systems but leaves concrete signatures in experimentally observable states.

1. Introduction
Topological systems with a chiral symmetry are intimately related to a supersymmetry, but this connection is often considered only for the mathematical understanding, and rarely exploited for concrete physical effects. Here I show that this structure directly affects the wavefunctions of topological states in ways that make them visible in experiments, and suitable for unconventional applications.

2. Background
Systems with a chiral symmetry are governed by an effective Hamiltonian $H$ that fulfills [1]

$$\Sigma H \Sigma = -H,$$

with a unitary involution $\Sigma$. This symmetry has important consequences as $H$ determines the spectral features of the system and generates its time evolution. Topological features occur when the signature $\text{tr} \, \Sigma = \nu$ is finite, as this guarantees the existence of $|\nu|$ zero modes with vanishing frequency.

A useful perspective to interpret these features starts by considering $\Sigma$ as a usual symmetry of $H^2$. Going from $H^2$ to $H$ then mathematically corresponds to a factorization as undertaken in supersymmetry (SUSY) QM [2]. Indeed, zero modes have a SUSY interpretation in terms of states localized in only one of the two sectors of the theory. This perspective is also useful to construct novel topological models [3], known as square-root topological insulators, as utilized in two recent experiments [4,5].

3. Results and discussion
To describe the universal utility of this perspective I describe it various settings. The first is strained photonic graphene, in which the topological states are pseudo-Landau levels (LLs) [6,7]. In the bulk, these states have been recently observed in two experiments [8,9]. I describe how all LLs display a characteristic mode structure that arises from SUSY [9]. In the second example, the SUSY interpretation applies to a topological zero mode in a CROW [10]. Here the SUSY mode structure of this mode can be exploited for diverse applications such as topological receiver-protectors [11] or topological defect-state lasers [10,12]. Finally, I describe how these effects translate to intrinsic degrees of freedom, as encountered in the polarization of photons in a quantum walks [13] and in the spin magnetization degree of freedom of electronic mesoscopic devices [14].

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References


Non-Hermitian Properties of Photonic and Plasmonic Nanocavities

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Abstract

Photonic and plasmonic micro and nanocavities confine light at a deep subwavelength scale but generally suffer from large radiative leakage and absorption losses. As a consequence, nanocavities are inherently non-Hermitian systems. The non-Hermitian character provides them peculiar properties, especially regarding the control of spontaneous emission. Quasinormal modes, i.e., natural eigenmodes of a non-Hermitian system, are the adequate tools for describing light-matter interactions in photonic and plasmonic nanocavities.

Quasinormal modes are the adequate tools that should be used to describe light-matter interactions in non-Hermitian resonant systems. We will show how they can be used to unravel the non-Lorentzian character of spontaneous emission and more generally local density of states in photonic and plasmonic nanocavities [5-7]. The non-Hermitian properties are all the more pronounced as the system supports several overlapping modes within a given spectral range.

References


Scattering properties of non-reciprocal systems with gain/loss

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Abstract
We develop a transfer matrix description for non-reciprocal media with gain and loss, and show how topological signatures in these systems can be detected in transport experiments. This includes signatures of the non-Hermitian skin effect, for which we clarify the role of scattering boundary conditions.

1. Introduction
In recent years, the scattering properties of non-Hermitian models attract the attention of physicists from photonics to condensed matter physics. For instance, spectral singularities are specific points of the continuous spectrum of complex scattering potentials where the transmission and reflection amplitudes diverge. These points are one of the peculiar spectral properties of non-Hermitian Hamiltonians which have been studied in optical models as a condition of lasing [1, 2]. The time-reversal of spectral singularity is responsible for the recently discovered devices called coherent perfect absorbers (CPA) or antilasers which is also investigated in an atomic Bose-Einstein condensate [3, 4]. Directional invisibility, reflectionless and transparency are also other transport characteristics of the non-Hermitian models [5].

These phenomena are investigated from both theoretical and experimental views in PT-symmetric models and also paved their way in the non-Hermitian tight-binding model lately [6, 7]. In these studies, the scattering matrix [8, 9] and the transfer matrix method (see [10] in linear models and [11] in nonlinear models) plays a key role to characterize these scattering phenomena. The entries of transfer matrix for a scattering potential are related to the transmission and reflection amplitudes, by using them we are able to define the appropriate conditions of scattering phenomena. Interestingly, the transfer matrix method also provides an analytic method for investigating topological effects such as non-Hermitian skin effect in non-Hermitian topological models [12].

In this presentation, we consider a non-reciprocal tight-binding model with on-site potential and apply the transfer matrix method to provide numerically the relevant range of the corresponding parameters of the model for different transport properties. We also study aspects of boundary conditions in topological characteristics of the system.

References

Nanoantennas with Balanced Gain and Loss

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Abstract

We will discuss how the addition of plasmonic elements with gain to conventional metallic nanoantennas can serve to achieve directional optical responses.

1. Discussion

Nanoantennas, as their macroscopic counterparts, are designed to couple subwavelength sources with free radiation, providing, at the same time, directionality to this interaction. Metallic nanoparticles constitute an ideal platform for the design of these devices thanks to their ability to support surface plasmons, the collective oscillations of conduction electrons. These excitations generate large and localized electric fields that enhance the coupling between subwavelength sources and free radiation. Here, we investigate the prospect of incorporating active materials, which display optical gain when externally pumped, to benefit the design of metallic nanoantennas. To accomplish this, we study the optical response of a dimer composed of two metallic nanoparticles, one with the usual passive response and the other doped with a gain material. This system has been shown to display highly anisotropic responses under plane wave illumination [1]. Similarly, when excited by a point dipole placed at the gap, we find that the presence of gain, in addition to mitigating the losses and therefore increasing the power radiated or absorbed by the dipole, introduces a phase difference between the elements of the nanoantenna that makes the optical response of the system directional, even in the absence of geometrical asymmetry [2]. Furthermore, since the level of gain can be externally controlled, the response of this nanoantenna is tunable. Exploiting these properties, we analyze how a pair of nanoantennas with balanced gain and loss can enhance the far-field interaction between two dipole emitters. As shown in Figure 1, when the pair is configured as loss-gain-gain-loss (LGGL) the transfer rate between the emitters placed at the gaps of the antennas can be several orders of magnitude larger than in vacuum. Furthermore, as the level of gain increases, the ratio between the transfer rates for the LGGL and GLLG becomes larger. The results presented in this work show that the combination of nanostructures displaying gain and loss provides a new mechanism to design nanoantennas capable of actively controlling light.

Figure 1: Energy transfer mediated by nanoantennas with balanced gain and loss. We plot the normalized energy transfer rate between two dipoles placed at the gaps of a pair of nanoantennas as a function of the level of gain. We compare two different configurations, as depicted in the upper panel. (Figure adapted from [2]).

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References


Non-conservative optics with dielectric metasurfaces

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Abstract

We introduce a general approach for tailored non-conservative transformations of polarization states of light based on scattering and interference from specially engineered nano-resonators in ultra-thin dielectric metasurfaces. We present theoretical and experimental results demonstrating the fundamentals aspects and potential applications of such metasurfaces. These include an optimal monitoring of deviations from a selected polarization, transformation of any input two-photon quantum polarization-entangled state to an arbitrary target state, and discrimination between a set of objects with different polarization characteristics.

1. Introduction

Nanostructured metasurfaces possess exceptional capabilities in the manipulation of both classical \cite{1} and quantum \cite{2, 3} light associated with its vectorial nature through the polarization degree of freedom. Indeed, harnessing the polarization of light is an enabling factor to versatile applications, ranging from sensing to microscopy.

We employ a recently developed conceptual approach for implementing arbitrary complex-valued birefringence with high-index dielectric nanostructured metasurfaces \cite{4} to demonstrate new regimes of polarisation control for enhanced measurements and unconventional interference with classical and quantum light.

2. Optimal monitoring of deviations from target polarization

A fundamentally and practically important task lies in determining a small deviation in the vicinity of an anchor elliptical polarization. On the other hand, the most convenient polarization measurements are performed in linear polarization basis, such as projections to horizontal (H) and vertical (V) polarization states. The dielectric metasurfaces without material absorption are most suitable for sensitive polarization detection even in low-light conditions, yet they often lack a chiral response. Therefore, a possibility to magnify small changes around arbitrary polarization states using non-chiral metasurfaces would boost the application of meta-optics for sensitive detection that is relevant to multiple aspects of polarization optics.

We develop an optimal design of monolithic non-chiral metasurfaces that can amplify small deviations in the vicinity of arbitrarily chosen polarization states, as outlined in Fig. 1. Our approach is applicable to monitoring circular, linear and...

Figure 1. Concept of sensitive polarization monitoring with metasurfaces. (a) An arbitrarily chosen elliptical anchor polarization shown by arrow on a Bloch sphere and deviations up to $|\delta|$ are indicated by shading. (b) A metasurface performing a special non-unitary transformation $T$. (c) The transmitted anchor state is converted to a horizontal polarization, with the vertical component representing amplified sensitivity to deviations by a factor $\alpha$. (d) Scanning electron microscope (SEM) image of a fabricated metasurface designed to resolve an anchor polarization state $\psi = [\cos(0.2\pi), \sin(0.2\pi)\exp(0.3i)]^T$ with the target sensitivity $\alpha = 10$. 
general elliptical polarizations, such as an example in Fig. 1(a) showing with an arrow on the Poincaré sphere a state vector $\psi$ representing an anchor elliptical polarization. A to-be-sensed quantity alters the anchor polarization by a small deviation $\delta$, bringing it to the perturbed state $\psi_p = \psi + \delta \tilde{\psi}$, where $\tilde{\psi}$ represents the orthogonal polarization of $\psi$.

We design a metasurface that realizes a transformation $T$ [Fig. 1(b)] according to the following guiding principles. First, it converts an input anchor polarization to the $|H\rangle$ state, such that the output $|V\rangle$ component is zero in absence of perturbations. Then, the deviations are associated with the appearance of output vertical polarization component, see Fig. 1(c), and their detection sensitivity can be defined as the corresponding ratio of V-H amplitudes. Accordingly, the second metasurface design goal is to increase the sensitivity to deviations by a factor $\alpha$, such that the ratio of vertical and horizontal components provides an amplified value of the deviation.

We achieve the optimal transformation $T$ with monolithic all-dielectric metasurfaces by non-trivially generalizing the use of pairwise structures, which we have developed for synthesizing the polarization-dependent diffraction loss [5]. An exemplary metasurface layout is shown in Fig. 1(d) with a unit cell consisting of two types of silicon nano-pillars. The shown structure enables amplified sensing of polarization deviations around a non-trivial elliptical polarization.

3. Arbitrary Transformation of Two-Photon Polarization-Entangled States

Manipulation of multi-photon states, especially in the commonly-used polarization degree of freedom, is an active research topic associated with a variety of emerging practical applications including quantum communications and simulations. The capacity to change the joint polarisation state of several photons and also vary the degree of quantum entanglement is essential for the preparation of target states. Traditionally, this is achieved with a series of bulk optical elements realizing rotations and post-selections, which restricts the stability and scalability outside the laboratory environment.

We develop a new approach for implementing metasurfaces that can directly transform a chosen entangled two-photon polarization state to another arbitrary target state. We demonstrate experimentally an important capacity for altering the angle between the pair of states on a Poincaré sphere, which can be used to modify the degree of quantum entanglement. This cannot be accomplished by unitary operators, and requires a non-Hermitian (i.e. non-conservative) transformation [6].

4. Discerning Polarization Objects using Non-local Measurements

There is a strong demand for efficient and integrated optical schemes performing characterization of objects with polarization-sensitive transmission characteristics, such as in biological samples, across a broad spectral range. We present an original non-local ghost measurement scheme incorporating specially designed highly transmissive dielectric metasurfaces, which enable accurate discrimination between a pre-trained set of objects with different polarization characteristics [7].

We demonstrate that both fully and partially transparent polarization objects can be discriminated with the help of metasurfaces incorporated in an original ghost measurement scheme. The proposed method can benefit a variety of applications demanding accurate discrimination of objects with various polarization characteristics.

5. Conclusions

We anticipate that this work will enable a new class of ultra-compact and ultra-sensitive flat meta-optical devices for a broad range of applications including advanced sensing, imaging, and metrology in both classical and quantum photonics.

Acknowledgements

This presentation is based on results of collaborations driven by researchers who co-authored Refs. [5-7].

References

Hiding Parity-time Symmetry by Transformation Optics

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Abstract

We investigate how exceptional points can be constructed by using transformation optics (TO). By transforming a seed structure with conventional PT symmetry, we theoretically generate non-Hermitian daughter systems which do not possess PT symmetry in the usual sense but with inherited exceptional points and PT-phase transitions.

1. Introduction

Exceptional points (EPs) have been extensively investigated with sensitive properties which allow applications like the realizations of ultrasensitive plasmonic sensors [1] and vortex beam generators [2], etc. One systematic way to construct EPs is to employ the PT symmetry to the coupled systems and sweep gain/loss or the coupling parameter. There are also alternative ways such as employing bianisotropy [3,4] and anti-PT symmetry in constructing a EP. In particular, EPs in anti-PT symmetric system is relatively recent and have been found in ring laser gyroscopes for enhancing Sagnac effect [5,6], and in side-coupled cavities for robust sensing [7] or electromagnetic induced transparency [8]. Following the spirit of the route that the conventional parity symmetry can be replaced by other kinds of symmetry, our work focuses on how the TO can help generate EPs. After applying TO on the seed structure with PT symmetry, the PT symmetry is effectively hidden in the daughter system, equivalently the P-operation is effectively coordinate-transformed. The EPs can still be captured in the daughter system which does not have the conventional PT symmetry [9].

2. Transformation optics on a PT symmetric structure

In this work, we consider transforming a metal-dielectric-metal (MDM) system as shown in Fig. 1(a) as the seed system. It consists of two semi-infinite metal slabs with loss (\(\varepsilon_L = \varepsilon + iy\)) and gain (\(\varepsilon_R = \varepsilon - iy\)) separated by a thickness (\(d\)) of vacuum with permittivity \(\varepsilon_0 = 1\). The system is PT symmetric, with P-operation being the mirror operation in the \(u\) direction and T-operation being conjugate operation, satisfying \(\varepsilon_R = \varepsilon_L^*\). Now we consider an example conformal mapping:

\[
\frac{z - ge^{-\frac{2\pi w}{\Lambda}w}}{\Lambda} = \frac{\Lambda z - g}{\Lambda w}
\]

which transforms the MDM structure in \(w\)-plane (\(w = u + iv\)) to the concentric shells in \(z\) plane (\(z = x + iy\)), as shown in Fig. 1(b). The principle of TO [10,11] allows us to get the permittivity and permeability according to \(\varepsilon' = \partial\lambda^T/\partial\lambda\), where \(\lambda = \partial(x,y)/\partial(u,v)\) is the Jacobian transformation matrix and \(\partial\lambda = [dz/dw]^2\). For the plasmonic system which has only the TM (transverse magnetic) mode, we only need to consider the in-plane permittivity and out-of-plane permeability. Since the mapping is conformal, the in-plane permittivity stays the same and isotropic (mapping orange to orange or blue to blue region) while the out-of-plane permeability is changed. However, if we consider the near-field approximation that the structure is much smaller than the wavelength, the change of permeability can be neglected [12].

Figure 1: Schematic diagram of the transformation from a MDM structure to a concentric shell structure.

3. Exceptional point dynamics in the transformed daughter system

We begin from the gap plasmon mode in the \(w\) plane with TM polarization satisfying the mode equation:
where the positive integer $m$ corresponds to the discretized linear momentum due to the artificially imposed period $H$ in the $w$ plane. According to TO, the same mode equation also describes the mode spectra in $z$ plane by replacing $\exp(4\pi nmd/H) \rightarrow R_z^{2m}/R_1^{2m}$ when the size of the shell is much smaller than the wavelength. Therefore, the exceptional point of the mother system should be inherited by the daughter system as they share the same mode equation. By substituting the Drude model for the original PT-symmetric system $\epsilon_L = 1 - \frac{k_y^2}{\epsilon_0^2 + 2i\omega\gamma}$ and $\epsilon_R = 1 - \frac{k_y^2}{\epsilon_0^2 + 2i\omega\gamma}$ into the mode equation, one can solve the mode wavenumber $k_y$ at different $\gamma$, as shown as the dashed line (analytic solution) in Fig. 2. The analytic solution clearly captures the exceptional point at $\gamma \approx 4.05 \times 10^4 \text{m}^{-1}$, at which two modes in the symmetric phase join into one branch through the exceptional point. On the other hand, the eigenmodes of the daughter system can be solved in the full-wave picture, including retardation effect, in formulating a secular determinant (using cylindrical harmonics) whose value becomes zero at plasmon modes. In actual calculations, we have applied a tiny perturbation of the permittivity on $\epsilon_R \equiv \epsilon_1 + \delta \epsilon$ to compromise on the effect of the retardation (with details not shown here). Such secular determinant is also plotted in Fig. 2 as the color map. The blue colors mean the zero value, i.e. where the modes should lie. The results show very good agreement with the analytic solution, indicating our design strategy in using TO to induce an EP from the parent to the daughter system.

![Figure 2](image-url) Exceptional point dynamics for solving mode equation with retardation effect for wavenumber $k_y$ against $\gamma$. The dashed line shows the analytic solution in solving Eq. (2) without retardation effect.

### 4. Conclusions

We have investigated TO approach to generate non-Hermitian systems by transforming a plasmonic metal-dielectric-metal structure and capture an exceptional-point inheritance. This approach can be generally applied to more complex geometries and other origins of EPs such as bianisotropic and anti-PT symmetric structures, providing an alternative method to design non-Hermitian plasmonic systems.

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Optical mode transfer by encircling fixed and moving exceptional points

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Abstract

We discuss recent progress on optical mode transfer in parity-time symmetric systems. We discuss structures where modes evolve in parameter space such that an exceptional point is encircled, and consider cases where the exceptional point is fixed or mobile. We also discuss prospects for realizing non-linear or active structures.

Synthetic optical materials having a carefully-structured complex refractive index distribution, following non-Hermitian Hamiltonian analogs, have attracted significant attention because of their interesting optical behaviour [1]. Such materials enable functions such as uni-directionality, non-reciprocity, and unconventional beam dynamics.

The interplay between gain and loss, especially in low-loss plasmonic systems is interesting because parity-time (PT) symmetric and exceptional point systems become readily accessible. Example systems include plasmonic waveguide Bragg gratings incorporating structured and unstructured gain media enabling distributed feedback lasing [2], and single-sided reflection [3]. Single-sided diffraction as a holographic lattice transitions through the exceptional point is also interesting [4].

We discuss recent experiments in silicon optical waveguides that confirm modal evolutions tracing out adiabatic and anti-adiabatic parametric paths around fixed [5] or moving [6] exceptional points. Such modal evolutions are reciprocal in the linear regime, but may become nonreciprocal in nonlinear or active cases, over a very broad optical bandwidth [7]. The prospects for achieving active performance are also discussed.

References

Synthesis and characterization of plasmonic nanostructures
Synthesis, characterization and example applications of anisotropic plasmonic metal nanoparticles

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Plasmonic metal nanoparticles can be used in various fields of science, including spectroscopy, catalysis, cancer detection and treatment, and many others. In some metallic nanoparticles, incident light of an appropriate frequency excites the collective oscillation of electron plasma, a phenomenon known as surface plasmon resonance (SPR). The position of an SPR peak depends on various factors such as size, shape, and the composition of the nanostructure. Electron plasma oscillations lead to a high local enhancement of the electromagnetic field. Theoretical calculations have shown that the highest enhancement occurs on sharp tops and edges in the case of anisotropic nanoparticles, or in the gaps between nanoparticles. Therefore, today many research groups continue to develop novel, highly efficient methods for the synthesis of anisotropic noble metal nanoparticles.

Herein, various methods of anisotropic noble metal nanoparticles synthesis are presented. Silver decahedrons can be synthesized, for example, using photochemical methods, while other nanoparticles such as nanorods, bipyramids or concave cube can be formed by the seed-mediated growth method. It has been found that the final geometry of the nanoparticles depends on many parameters such as temperature, pH, the crystal phase of the seeds, or presence of certain metal ions. The nanoparticles obtained have been used, for example, as optical nanoresonators for SERS measurements. It has been found that, in some cases, anisotropic noble metal nanoparticles were almost ten times more effective than standard semi-spherical nanoparticles. Therefore, the application of anisotropic plasmonic metal nanoparticles in SERS measurements makes it possible to achieve a significantly higher SERS enhancement factor, which in turns makes it possible to detect analytes in a lower concentration range. However, direct interaction between the metallic surfaces and some analytes could lead to their denaturation. Therefore, in some cases, nanometric layers composed of a protecting oxide are deposited on the nanoparticle surface. The protective layer keeps the nanoparticles from agglomerating and prevents any direct interaction between the metallic surface and the analyte molecules. It has been found that, even after the deposition of a nanometric oxide layer, the nanoparticles can still be used as optical nanoresonators. Examples of the synthesis of such core-shell plasmonic structures will be presented.

Recently, many research groups have tried to applied nanoparticles in the diagnostic and treatment of cancer. It has been reported that plasmonic noble metal nanoparticles can be used as new kinds of photosensitizers instead of the standard, organic ones. In such cases, the excitation energy from noble metal nanoparticles can be transferred to an oxygen molecule in the triplet, ground state, which leads to a relaxing of the nanoparticles and the formation of highly cytotoxic excited oxygen molecules in the singlet state. Plasmonic anisotropic noble metal nanoparticles exhibit many properties that make them promising photosensitizers. Examples of possible applications of plasmonic nanoparticles in cancer treatment are also discussed.
Plasmonics in a Variable Temperature Thermodynamic Bath

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Abstract

Electromagnetically-heated metal nanoparticles can be exploited as efficient heat sources at the nanoscale. The assessment of their temperature is, however, often performed indirectly by modelling their temperature-dependent dielectric response. Direct measurements of the optical properties of metallic nanoparticles in equilibrium with a thermodynamic bath provide a calibration of their thermo-optical response, to be exploited for refining current thermoplasmonic models or whenever direct temperature assessments are practically unfeasible.

1. Introduction

In thermoplasmonics, the dissipation of electromagnetic energy within metallic nanoparticles (NPs) is exploited to generate heat on a local scale, remotely controlled by the exciting light. The actual temperature achieved within a NP, or in its close surrounding, is however often indirectly inferred, or estimated through more-or-less complicated models. In order to improve the precision in these estimates, however, it would be of considerable interest to independently know the temperature dependence of the plasmonic response of these nanosystems. To this end, we chose to investigate the plasmonic response of supported arrays of Au and Ag nanoparticles nanoparticles in a variable-temperature thermodynamic bath with temperature from room temperature to 350 °C [1,2]. We found that significant modifications of the optical response are introduced by temperature, depending on the system under scrutiny. This information can provide useful for the refinement of existing theoretical models and for calibrating with larger accuracy any thermoplasmonic experiment.

2. Experimental

2.1. Fabrication

The systems under scrutiny are 2D arrays of metal NPs obtained by template-assisted physical deposition followed by thermal dewetting (Fig. 1).

The arrays were fabricated depositing the target material onto the self-organized nanometric uniaxial sawtooth pattern that develops upon high-temperature homoepitaxial growth onto LiF(110) substrates [3]. Few nm of metal (typ.<5nm) were deposited at room temperature in high vacuum by molecular beam epitaxy at 60° of incidence with respect to the surface normal, and the samples were subsequently annealed at T=670 K in order to induce the thermal dewetting. Selected examples of array morphology are reported in Fig.1.

![Figure 1: 2D arrays of metallic nanoparticles supported on nanopatterned insulating substrates (1×1 μm²).](image)

The typical NP size achievable is of the order of 10-30 nm, whereas the areal density typically exceeds 10¹¹ NP/μm². The arrays are homogeneous over the whole sample area (typ. 1 cm²), making it straightforward to measure their properties without resorting to microscopy.

2.2. Temperature-dependent plasmonic response

The temperature dependent plasmonic response was measured within a home-made high-vacuum chamber allowing spectroscopic ellipsometry and transmittance spectra to be acquired as a function of variable sample temperature [4]. In the case of Au NP arrays, the plasmonic response of the system was assessed by spectroscopic ellipsometry performed under high vacuum conditions, as a function of the temperature of the sample. A model explicitly including the temperature-dependent dielectric function of the metal and finite-size corrections to the nanoparticles’ permittivity correctly reproduced experimental data for temperatures up to 75 °C. The model accuracy gradually faded for higher temperatures. (see data at 350°C reported in Fig. 2)

Introducing a temperature-dependent correction that effectively mimics a surface-scattering-like source of damping in the permittivity of the nanoparticles restored
good agreement with the data. A finite-size thermodynamic effect such as surface premelting may be invoked to explain this effect.

Figure 2: ellipsometric spectra of Au NP arrays at 350°C (red symbols). Theoretical model w/o surface premelting (dashed line). Theoretical model including surface premelting of Au (continuous line).

In the case of Ag NPs, we measured the temperature-dependent spectral transmittance as a function of temperature for a sample that had been previously exposed to atmosphere for a time of a few weeks (Fig.3). At room temperature, the sample showed a marked absorbance peak at 430 nm. For increasing temperature, a marked blueshift of the plasmon peak is observed, until a value around 400 nm is achieved at 380°C. Upon returning to room temperature, the spectral position of the peak is preserved, while an increased magnitude and a spectral narrowing is observed. The overall behavior is interpreted in terms of the decomposition of the Ag tarnish layer that spontaneously forms on Ag in atmosphere. Upon decomposition of this layer, the plasmon resonance blueshifts. Once the thermal decomposition is complete, returning to room temperature while maintaining the sample in high vacuum does not re-establish the tarnish layer, so the plasmon maintains its spectral position. The spectral narrowing arises due to the decreased dissipation at room temperature.

Figure 2: absorbance spectra of arrays of Ag NPs as a function of increasing temperature (RT to 380°C, violet to red lines). The dashed black line represents the absorbance.

Acknowledgements

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References


Spark discharge synthesis of noble metals and GeSi nanoparticles for UV-vis-NIR plasmonics

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Abstract

Noble metals (Pt, Au and Ag) and alloy GeSi aerosol nanoparticles were synthesized by spark discharge in pure argon atmosphere with additional in-flow sintering of nanoparticles at temperatures from 25 to 950 °C. The size, morphology, crystal structure and optical properties of obtained nanomaterials were investigated. It has been established that the thermal treatment of aerosol nanoparticles leads to crucial change in absorption properties and vary the morphology from branched agglomerates to spherical nanoparticles.

1. Introduction

Spark-discharge synthesis is a cost-effective and versatile method for production of metal, semiconductor, metal oxide and alloy nanoparticles [1, 2]. It enables the preparation of powders with high chemical purity during the erosion of electrodes in various gas atmospheres, such as air, argon, nitrogen, also the size, morphology and optical properties of nanoparticles can be controlled by additional sintering process of nanoparticles at high temperatures directly in gas flow [3]. Spark discharge is known as method for generation alloys nanoparticles from immiscible materials, for example, Ag – Cu, Au – Pt, Cu – W [4], Ge-Sn [5] by simultaneous electrical erosion of electrodes of different materials. This technology was successfully applied for producing platinum and tin oxide nanoparticles for gas sensors application and production of stable inks for jet printing [6]. Silver and copper airborne nanoparticles were used as a source for dry aerosol printing for creation microstructures on glass and plastic substrates [7, 8].

In this regard, the spark discharge synthesis can become a simple method of producing nanoparticles with unique optical properties and developing of plasmonic microstructures by aerosol jet printing, for example, for Surface-enhanced Raman spectroscopy (SERS) and luminescence applications.

2. Nanoparticles’ synthesis and characterization

2.1. Materials and Methods

In this work, we investigated the size, morphology and optical properties of germanium-silicon, platinum, silver and gold nanoparticles prepared by in-house developed spark discharge generator in the atmosphere of argon. For producing GeSi alloy germanium cathode and silicon anode were ablated simultaneously. Two electrodes of similar materials were used to prepare noble metal nanoparticles. The spark discharge process was carried out with the following conditions: pulse repetition rate of 500 Hz at a voltage of 1.5 kV in an argon gas (purity 6.0) flow 1 L/min. Nanoparticles aerosol passed through a custom-build tube furnace with the various temperatures from 25 to 950 °C and then were collected on a nanofiber filter AFA-RMB-20 and TEM copper grid with carbon film.

The microscopy studies were carried out on transmission electron microscopy (TEM) Jeol JEM 2100 (200 kV) with energy dispersive X-ray spectrometer X-MAXNOXFORD Instruments. The UV-vis-NIR spectra of nanoparticles were obtained using JASCO V-770 spectrophotometer. The agglomerates size distribution in the flow was measured using a TSI SMPS 3936 Aerosol spectrometer.

2.2. Size and optical properties of nanoparticles

According to TEM images primary particles of Au, Ag, Pt and GeSi nanomaterials, synthesized in spark discharge, have the sizes from 5 to 25 nm and form large submicron agglomerates and/or aggregates with mean size at the range from 280 to 380 nm depending on material. Most of the particles, additionally sintered at the temperatures upper 750 °C, are individual and characterized by spherical shape and diameters from 30 to 150 nm. Typical TEM images of GeSi and Au nanoparticles before and after in-flow sintering at 950 °C are shown at the Figure 1.
Conclusions

We demonstrated the possibility of synthesis of platinum, silver and gold nanoparticles by spark discharge, which characterized with surface plasmon resonance absorption peak position at 273, 423 and 493 nm, correspondingly. We have been established that in-flow gas thermal treatment of GeSi lead to dramatically change in particle morphology and shape of absorbance spectrum of alloy nanoparticles. Germanium-silicon nanoparticles agglomerates, synthesized at 25 °C had a uniformly decreasing wavelength dependence of absorption, whereas after thermal treatment the absorbance spectrum of GeSi was described by maximum at 620 nm and long absorption tail in infrared spectral region.

Acknowledgements

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References

Colloid- and Polymer-Based Self-Assembled Meta-atoms and Metasurfaces

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Abstract

We present some examples of meta-atoms and metasurfaces fabrication processes, which implement a bottom-up approach based on colloid and polymer directed self-assembly. Scalability and tunability of the processes are demonstrated, as well as the final optical properties reached by these self-assembled nanostructures.

1. Introduction

Since the emergence of the field of metamaterials in the 2000s7, artificial nanomaterials for optics have relied on assembled optical resonators as elements interacting so strongly with light that their scattering cross-sections largely exceed their geometrical sections over a finite bandwidth. Today, a wide range of nanoobjects, exhibiting plasmonic or Mie resonances, is available [1-3]. This presentation aims at pointing out how colloid- and polymer-based chemical engineering processes offer exciting routes to tailor the optical response [2-5], including polarizabilities, multipolar content, operation frequency, bandwidth and scattering diagram of the nanoobjects; and transmission, absorption, phase shift of their plane assemblies aiming at metasurfaces (MS). We will discuss examples where bottom-up synthesis and assembly of tailored nanoresonators have led to promising optical properties, specifically using self-assembled soft matter systems such as emulsions [4] and block copolymers [6,7].

2. Tailored self-assembled nanocolloidal Huygens scatterers in the visible

Existing nanocolloidal optical resonators exhibiting strong magnetic resonances often suffer from multistep low yield synthesis methods as well as a limited tunability, particularly in terms of spectral superposition of electric and magnetic resonances, which is the cornerstone for achieving Huygens scatterers. To overcome these drawbacks, we have synthesized clusters of gold nanoparticles using an emulsion-based formulation approach. This fabrication technique involved emulsification of an aqueous suspension of gold nanoparticles (NP) in an oil phase, followed by controlled ripening of the emulsion. The structural control of the as synthesized clusters, of mean radius 120 nm and produced in large numbers, is demonstrated with microscopy and X-ray scattering techniques. Using a polarization-resolved multi-angle light scattering setup, we conduct a comprehensive angular and spectroscopic determination of their optical resonant scattering in the visible wavelength range. We thus report on the clear experimental evidence of strong optical magnetic resonances and directional forward scattering patterns. The clusters behave as strong Huygens sources. Our findings crucially show that the electric and magnetic resonances as well as the scattering patterns can be tuned by adjusting the inner cluster structure, modifying a simple parameter of the fabrication method. This experimental approach allows for the large scale production of nanoresonators with potential uses for Huygens metasurfaces.

Figure 1: Top: Cryo-TEM micrographs of a gold NP-cluster under several incident angles, show the structure compactness. The bar is 100 nm. Bottom: Log-scale polar plot of the light scattered by clusters of increasing gold volume fraction \( f (= 0.18, \lambda = 620 \text{ nm, green}; f = 0.27, \lambda = 620 \text{ nm, red}; f = 0.46, \lambda = 650 \text{ nm, blue}) \).
3. Thin Perfect Absorber via Block Copolymer Engineered Metasurfaces

In another example, we report the experimental demonstration of an ultrathin metallic MS absorber system with perfect visible absorption. A recent interest has been focused on MS perfect absorbers [8–10], in which light can be absorbed in very thin layers of matter (thinner than visible wavelengths) for use in modern devices. An ordered porous matrix designed by block copolymers (BCPs) was used as a host template to engineer ultra-thin absorbing gold (Au) dots with heights from 5 to 15 nm and sub-50 nm diameters. The absorber based on a strong coupling design is composed of an Au dot hexagonal array on top of an alumina spacer, deposited by Atomic Layer Deposition and of controlled thickness, and a reflecting Au mirror. The versatile BCP-based nanofabrication strategy is tailored to achieve near-perfect absorption at \( \lambda = 570 \) nm. The optimal dielectric spacer thickness is larger than expected from numerical results by a finite element method, which we relate to an effect of smooth shapes of the gold dots. The experimental insight described in this work is a significant stride towards realizing large area flat optics applications.

4. Conclusions

The bottom-up approach brings a significant contribution to the design and generation of meta-atoms and metasurfaces. The main advantages are its ability to produce large amounts of meta-atoms and large area nanostructures, and its cost- and energy-effectiveness.

Tunability was demonstrated in several examples, and the tool-box of the classical colloidal and polymer physical-chemistry opens many opportunities for exploring efficient and applicable nanostructures.

Acknowledgements

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References

Synthesis and characterization of palladium nanoparticles by laser ablation in liquids

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Abstract

The outstanding catalytic and electronic properties of palladium nanoparticles, make them useful in a wide variety of applications including the biomedical field. In this work, palladium nanoparticles are obtained by laser ablation in water and methanol with two different laser sources (a Green nanosecond and a IR picosecond laser) and their physical-chemical properties are analyzed.

1. Introduction

Palladium is a transition metal with the lowest melting point and density of the platinum group. Additionally, its extraordinary ability to stabilize a large variety of matter states, confers it a great versatility. Regarding the nanoscale, their electronic and structural features enable a large variety of catalytic and electroanalytical applications [1,2].

Among the different methods for producing nanoparticles, laser ablation technique allows obtaining NPs without any precursor or chemical reactions. In previous works, other noble metal nanoparticles such as Ag [3,4] and Cu [5,6] were obtained by means of laser ablation in different media, showing how the characteristic features of the obtained nanoparticles can be controlled by varying the laser parameters and the medium properties. In the present work, palladium nanoparticles were produced by using the laser ablation technique in water and methanol with two different laser sources for a complete characterization.

2. Materials and methods

Palladium foils with 99.99% of purity were used as laser ablation target. Tests were carried out with 2 different laser sources in 2 liquid media, resulting in 4 samples as indicated in Table 1.

Table 1: Samples produced and analyzed.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Laser source</th>
<th>Liquid medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Green - ns</td>
<td>water</td>
</tr>
<tr>
<td>b</td>
<td>Green - ns</td>
<td>methanol</td>
</tr>
<tr>
<td>c</td>
<td>IR - ps</td>
<td>water</td>
</tr>
<tr>
<td>d</td>
<td>IR - ps</td>
<td>methanol</td>
</tr>
</tbody>
</table>

The first laser source was a nanosecond laser providing pulses at 532 nm of wavelength (Green – ns) with 0.26 mJ of pulse energy and 14 ns of pulse duration. The second laser source was a picosecond laser emitting radiation at 1064 nm (IR – ps), with 0.03 mJ of pulse energy and 800 ps of pulse duration.

Pure deionized water and methanol were used as solvents in the laser ablation process. Therefore, samples of the obtained nanoparticles in colloidal solution were deposited on carbon-coated copper microgrids for examination. Nanoparticle morphology and crystalline structure, by means of Scanning Electron Microscopy (SEM), High Resolution Transmission Electron Microscopy (HRTEM) and Selected area Electron Diffraction (SAED). In order to elucidate the crystalline phases, X-ray diffraction (XRD) was also performed.

The UV–Vis absorption spectrum of the palladium nanoparticles in colloidal suspension was measured in the range from 190 to 800 nm by means of UV–Vis spectrophotometry.

3. Results and Discussion

SEM and HRTEM allowed to perform an analysis of morphology and size distribution of the nanoparticles obtained. As shown in Fig. 1, Pd nanoparticles obtained are spherical, with certain tendency to agglomeration forming chain-like nanostructures. In terms of size, those obtained in methanol
are smaller than in water under the same conditions of laser parameters. This effect is due to the presence of carbon species which cover the surface of the embryonic particles during the growth process. The ones obtained with the Green – ns laser have a more homogeneous size distribution.

Figure 1: SEM micrographs of Pd nanoparticles obtained by laser ablation using (a) pulse nanosecond laser in water, (b) pulse nanosecond in methanol, (c) pulse picosecond laser in water, (d) pulse picosecond in methanol.

The optical response of the Pd nanoparticles in suspension was measured by means of UV- spectroscopy, showing a peak in the UV region around 220 nm (Fig. 2). In case of samples obtained in water, the absorption peak is slightly red-shifted, which is indicative of oxidation.

Figure 2: UV-vis spectrum of the obtained Pd nanoparticles.

The crystallinity of the obtained nanoparticles was confirmed by HRTEM. The measured interplanar distances obtained by SAED were indexed as metallic Palladium with the presence of palladium oxide in case of using water as solvent. XRD technique, corroborated the results given by the electronic microscopy.

4. Conclusions

Crystalline palladium nanoparticles without any additional chemical compound have been successfully obtained by laser ablation technique. Those obtained with the Green nanosecond laser are more homogeneous in size. Methanol acts as stabilizer during the formation process, controlling the nucleation process and preventing the nanoparticles from oxidizing.

Acknowledgements

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References


Synthesis of gold nanoparticles using α-amino acids

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Abstract

Various α-amino acids have been used as reducing and stabilizing agents in the synthesis of gold nanoparticles following the Turkevich protocol. The shape, size distribution, stability and optical properties of synthesized nanoparticles were characterized by SEM, DCS, PALS technique and UV-vis spectroscopy. The differences in chemical structure of α-amino acids strongly affect their reactivity and influence the shape, size distribution and stability of synthesized gold nanoparticles.

1. Introduction

Gold nanoparticles (AuNPs) have been the object of intense studies due to their unique properties,[1] mainly optical, which make them potentially useful for many applications including organic solar cells,[2] sensory probes,[3] surfaced enhanced Raman spectroscopy (SERS),[4] therapeutic agents,[5] catalysis,[6] and others. In any application, the AuNPs of certain size, shape, surface chemistry, or aggregation state will be needed. Therefore, synthetic protocols for fabrication of AuNPs with desired characteristics need to be developed.

There are several well-established protocols for synthesis of AuNPs including probably one of the most often used, the Turkevich method.[7] In this method, chloroauric acid is reduced with citrate ions, which also stabilize AuNPs fabricated in this reaction. The Turkevich method allows for reproducible synthesis of monodisperse quasi-spherical AuNPs of which size can be controlled by change of the reagents’ concentrations ratio. Nowadays there is a significant interest in the, so called green synthesis methods, where biological systems such as yeasts, fungi, bacteria, and plant extracts are used to synthesize nanoparticles.[8] The simplest reducing agents of biological origin are α-amino acids (α-aa), which show structural similarity with citrate or other α-hydroxy acids with respect to functional groups important for reduction and stabilization processes.[9] The α-amino acids have already been used for synthesis of AuNPs, however, there were only a few comparative studies for all of them.[10]

The goal of our studies was to investigate how the chemical structure of α-amino acids affects their reactivity toward chloroauric acid and how it influences the shape, size distribution and stability of synthesized gold nanoparticles. All syntheses were carried following the Turkevich protocol in which citrate was replaced by α-amino acids. The shape, size distribution, stability and optical properties of gold nanoparticles were characterized by scanning electron microscopy (SEM), differential centrifugal sedimentation (DCS), phase analysis light scattering (PALS) technique and UV-vis spectroscopy.

2. Experimental section

Amino acids (L-Alanine, L-Arginine, L-Asparagine, L-Aspartic acid, L-Cysteine, L-Glutamic acid, L-Glutamine, Glycine, L-Histidine, L-Hydroxyproline, L-Isoleucine, L-Leucine, L-Lysine, L-Methionine, L-Phenylalanine, L-Proline, L-Serine, L-Threonine, L-Tryptophan, L-Tyrosine, L-Valine), sodium hydroxide, sodium bicarbonate and gold(III) chloride were purchased from Merck. The purchased amino acids were converted to corresponding salts by reacting them with sodium hydroxide or sodium bicarbonate. Ultrapure deionized (DI) water was used throughout the experiments. All glassware was treated before the reactions with aqua regia for 5 min and rinsed several times with DI water.

The solutions of AuNPs were prepared following the method described by Turkevich.[7] In a typical procedure, a 3 mL sample of aqueous HAuCl₄ (5 mM) was added to a 250 mL flask containing 54 mL of water at room temperature. The solution was brought to a boil while stirring magnetically (400 rpm) and then 3 mL of 0.02 M reducing agent (salt of amino acid) solution was added at once.

Scanning electron microscope (SEM) images of AuNPs were obtained using an FEI environmental SEM (Quanta 250 FEG). AuNPs size distributions were determined by the Differential Centrifugal Sedimentation (DCS) technique using a CPS Disc Centrifuge MOD DC24000 UHR (CPS Instruments Inc.). Zeta potential measurements, providing information about colloidal stability, were carried out by phase analysis light scattering (PALS) technique using a NanoBrook Omni (Brookhaven Instruments) instrument with a 640 nm diode laser. The absorption spectra of AuNPs suspensions were measured at room temperature using a Lambda 650 UV-vis spectrophotometer (Perkin Elmer) in the 250 – 850 nm spectral range.

3. Discussion

In our studies, we have used twenty naturally-occurring α-aa and L-Hydroxyproline for synthesis of AuNPs following Turkevich protocol. The α-aa have common structural features, carboxylic group and amino group in α-position, which are important for both reduction and stabilization processes. However, there are also additional functional
groups, which have been shown to strongly affect the chemical properties of studied α-aa. In our studies, each α-aa was first treated with either NaHCO₃ or NaOH to convert it to desired ionic form and then has been used for reduction of chloroauric acid. For all α-aa we have used the same conditions. Among 21 used α-aa, 18 has yielded products of reductions, either stable or non-stable which aggregated shortly after reaction. Among 18 successful reductions, most of the syntheses have yielded quasi-spherical AuNPs as it is shown for L-Valine in Figure 1.

In conclusion, we have investigated how the chemical structure of α-amino acids influences the shape, size distribution and stability of AuNPs synthesized via Turkevich protocol. The side chains in α-amino acids have a strong influence on their chemical properties, which have been reflected in the results of our studies. The reduction has not occurred in case of three α-aa, L-Cysteine, L-Proline and L-Glutamine. L-Arginine, L-Tyrosine and L-Histidine have yielded nanostructures of irregular shape. The remaining α-aa have yielded AuNPs of regular shape.

Acknowledgements

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References

Mesoscale Plasmonics, Nanophotonics and Acoustics
Super-enhancement focusing of Teflon sphere in terahertz band

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Abstract
A Teflon sphere can focus the light near its shadow surface. In this paper, two circular hotspots having the extremely large field-intensity were discovered around the poles of a specifically sized Teflon sphere irradiated by a plane wave in terahertz band using an analytical algorithm. A huge contribution of scattering amplitude from a single order of mode in electric-field or magnetic-field is considered as the main factor to trigger this phenomenon of super-enhancement focusing.

1. Introduction

Lord Rayleigh stepped forward to the scattering study by the small particles and found that a small dielectric particle with a radius, \(a\), that is much smaller than the wavelength, \(\lambda\), can symmetrically scatter light in the forward and backward directions functioning like a point electric dipole [1]. Lorenz-Mie theory fully describes the optical absorption and scattering of light by a homogeneous sphere, which verifies that an asymmetrical jet-like near-field focus only situates near the shadow surface of the sphere in the certain range of \(a/\lambda\) (could not be too small) [2]. Such kind of focus has been well studied since 2000 [3]. The corresponding jet-like focus can propagate with a little divergence for the distance of several wavelengths and possibly form a super-resolution optical system when its transverse dimension determined by the full width at half maximum (FWHM) is shorter than the diffraction limit. Many approaches were carried out to further enhance the field-intensity of this jet focus and narrow its transverse dimension, but most of them required to change the geometry or the material properties of the sphere.

In terahertz (THz) band, Teflon is one of the widely-used low-loss materials to make lenses or probes in sensing and imaging applications due to its outstanding performance and low-cost advantage. Compared with superlens made of the lossy metals, Teflon spherical superlens is not limited by the intrinsic loss, which mainly benefits from the extremely low extinction coefficient, \(k\), of Teflon material. In this paper, we extend our research scope to include loss impact on the formation of a super-enhanced focus by using a Teflon sphere. This topic has not been deeply explored before. Notwithstanding it is well known that \(k\) of Teflon approximately equals to 0, its precisely measured values are diverse in the previous literatures [4]. Consequently, the focusing parameters, including peak \(E^2\) field-intensity, FWHM, and the focal length, are analytically calculated based on 4 Teflon \(k\) values with the different magnitudes (ideal non-loss \(k = 0\), other three are from publications) within a range of size parameter of Lorenz-Mie theory, \(q\), between \(\pi\) and \(20\pi\). The near-field intensity distributions and the corresponding scattering amplitudes of each order of mode are realised at the specific super-enhancement \(q\) values to analyse the influence of the loss in this phenomenon.

2. Results

Fig. 1 (a) summarises the peak field enhancements of focus by a Teflon sphere with \(k = 0\), \(1.40 \times 10^{-4}\), \(5.95 \times 10^{-4}\), and \(1.70 \times 10^{-3}\), respectively, as a function of \(q\). An increasing tendency is manifested with the regular oscillations for all 4 curves in Fig. 1 (a). Several super-enhancement giant peaks appear in the curves of \(k = 0\) and \(1.40 \times 10^{-4}\) in Fig. 1 (a), especially for the ideal non-loss case \(k = 0\) which has more super-enhancement \(q\) positions and the highest giant peak. Meanwhile, growth of Teflon loss representing as the increase of \(k\) value effectively weakens the aforementioned sharp rising features, which reflects on the less fluctuant curves of \(k = 5.95 \times 10^{-4}\) and \(1.70 \times 10^{-3}\) in Fig. 1 (a) and their near-field field-intensity distributions in Fig. 1 (b) and (c). \(E^2\) field-intensity distributions of a super-enhancement position \(q = 22.24159\) in \(xz\) plane are manifested in Fig. 1 (b) and (c) with the \(k\) values 0 and \(1.7 \times 10^{-3}\), respectively. Maximum super-enhancement of \(k = 0\) reaches 440 in Fig. 1 (b), and two symmetric hotspot focuses situate at the poles of the sphere. This layout of focus was never reported before. However, it is found that intensity of the top hotspot tends to decrease with the growth of \(k\) value, finally, the layout of two polar hotspots vanishes when \(k\) is \(1.7 \times 10^{-3}\), as shown in Fig. 1 (c).

3. Discussion

Peak field enhancement in Fig. 1 (a) is the collective outcome of the near-field electric resonance and magnetic
resonance from the multiple orders of modes. To calculate the scattering amplitude at each order of mode \( l \) is beneficial to investigate the physics behind the super-enhancement focusing of the sphere with the specific \( q \) value. According to the Lorenz-Mie theory, scattering amplitudes are classified by external and internal fields. The external scattering amplitudes \((a_l, b_l)\) for electric-field, \((c_l, d_l)\) for magnetic-field) and the internal scattering amplitudes \((d_l, e_l)\) for electric-field and \((c_l, f_l)\) for magnetic-field) are well defined in the literature [2]. The corresponding scattering amplitudes for the spheres with two super-enhancement \( q \) values of 22.24159 and 28.64159 are demonstrated in Fig. 2 (a) and (b) compared with those for the neighbouring normal \( q \) values. It is found that order of mode \( l = 27 \) provides an impressively sharp raise of scattering amplitude, \( d_l \), in the internal electric-field reaching about 240 for \( k = 0 \) at the super-enhancement position \( q = 22.24159 \), as shown in Fig. 2 (a). By contrast, for the sphere with \( q \) value of 28.64159 the giant scattering amplitude peak locates at \( l = 35 \) for the internal magnetic-field \( c_l \), with a massive value of 1700, as shown in Fig. 2 (b).

Fig. 2 (a) Scattering amplitudes, \( d_l \), for internal electric-field against order of mode, \( l \), for the sphere with \( q = 22.24159 \) (b) Scattering amplitudes, \( c_l \), for internal magnetic-field against order of mode, \( l \), for the sphere with \( q = 28.64159 \)

4. Conclusions

In this study, we use an analytical algorithm to systematically investigate the super-enhancement focusing happened in the Teflon spheres with the specific size parameters. Attenuation of the intensity of the top hotspot in the layout of double polar hotspots can affect the strength of this effect in the near-field distribution with the growth of the loss. The calculated scattering amplitudes indicate that the internal resonance at a certain high order of mode results in this phenomenon, and it can be triggered by either electric-field or magnetic-field.

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References

High Intensity Photonic Nanojets from a Gradient Low Refractive Index Profile

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Abstract

Designs for photonic nanojet (PNJ) generators are examined. The maximum intensity of the PNJ is used as an objective for optimization under the constraint of maximum refractive index and fixed generator size. Building on the work of Patel et al. with a generator of a step-index profile across tangent microspheres, we propose a gradient index (GRIN) design. Our design has a higher intensity focus yet requires lower index contrast. This eases fabrication while improving resolution in applications including photolithography.

1. Introduction

A photonic nanojet (PNJ) is a non-evanescent beam of light with a subdiffraction width that propagates over a distance greater than one wavelength. A few important characteristics of the PNJ must be defined [1]. The location of maximum intensity in the PNJ is referred to as the hot spot. The width is measured as the full-width at half maximum (FWHM) intensity in the transverse plane that includes the hot spot. The length is determined as the distance from the hot spot to a decrease of \( \frac{1}{e} \) in intensity. The working distance is the distance from the surface of the generator to the hot spot.

Applications of PNJs include manipulation and detection of nanoscale objects in the fields of physics and biology. Tight light concentration is beneficial for nonlinear optical applications. In particular, high resolution photolithography and imaging with PNJs beyond the classical diffraction limit is possible [2]. Furthermore, by producing PNJs of smaller FWHM or higher intensity hot spots, this resolution may be increased.

A crescent-shaped step-index profile has been shown to produce a smaller FWHM and higher intensity at the hot spot than a microcylinder of constant refractive index. That design used several microspheres of discrete refractive index values. When the index is constrained such that \( n \leq 1.7 \), and the device is illuminated with 500 nm light, a FWHM of 152 nm (\( \lambda/3.29 \)) is produced [3].

2. Theory

To further improve hot spot intensity and narrow the FWHM, we consider the case where infinitely many tangent microspheres of varying index are placed together. This changes the index profile to a gradient index (GRIN), allowing simulations to be performed with an adjustable mathematical function for the index, e.g. Equation (1). The mathematical function is designed such that any point on a given circle tangent to the origin has the same refractive index. To allow for convergence of refractive index to a value of \( a + b \) at the origin, we add a regulation factor \( \epsilon \). Finally, we multiply by a step function, Equation (2), to limit our outermost microsphere to a radius \( r \). The sphere is created in the half-plane where \( y < 0 \).

\[
\begin{align*}
n(x, y) &= a + \text{step}(x, y) \left[ \frac{\epsilon(|y| + \epsilon)}{x^2 + (|y| + \epsilon)^2} \right]^{1/m} \\
\text{step}(x, y) &= \begin{cases} 
  b & (x^2 + (y + r)^2) \leq r^2 \\
  0 & (x^2 + (y + r)^2) > r^2 
\end{cases}
\end{align*}
\]

where \( a, b, \) and \( r \) are fixed values, and \( m \) is the parameter to be optimized.

![Figure 1: (a) 2D Heatmap of Structure’s Refractive Index. (b) Plot of refractive index versus vertical position. In subfigure (a), the bottom of the sphere corresponds to \( x = 0, y = -1 \), and the top of the sphere corresponds to \( x = 0, y = 0 \).](image-url)
To best compare our PNJ generators against those in the literature, we will use a similar set of parameters. The device is illuminated with a 500 nm plane wave. We choose $\epsilon = 10^{-2} \mu m$. The coefficients were set due to physical constraints to $a = 1$ and $b = 0.7$. The parameter $m$ was optimized to a value of 46.44 which maximizes intensity. We will constrain our GRIN devices to have a 1.5-µm radius and maximum index of 1.7. Although the range of indices is accessible with porous dielectrics, the GRIN geometry will require a nonstandard fabrication process. Figure 1 (a) demonstrates the index profile qualitatively, while Fig. 1 (b) quantifies the index profile along the $x = 0$ line.

3. Simulations

All simulations were performed in 2D with COMSOL Multiphysics 5.4. COMSOL uses finite-element method (FEM) to perform wave optics simulations. An environment of 5.5 by 9 microns was used, with a perfectly matched layer (PML) of 1 micron extending beyond that around three edges. The end of the PML was set to a perfect electric conductor. An electric field source of amplitude 1 and wavelength 500 nm was placed at the fourth edge. Figure 2 (a)-(c) provides a qualitative view of the simulation results, while Fig. 2 (d) demonstrates the quantitative results.

As Fig. 2 (d) shows, the intensity profile for the GRIN PNJ has a higher peak than a similar step-index crescent or constant index design. The GRIN PNJ produces a FWHM of 143 nm ($\lambda/3.51$) and a hot spot intensity 45.3 times larger than the incident wave. The hot spot of the GRIN PNJ is 2.04 times more intense than the PNJ from the step-index design.

4. Discussion

The structure has been optimized for fabrication through any process that can produce GRIN optics. The indices for the final device range only between 1.63 and 1.70, which are accessible with silicon oxynitride (SiOxNy). An index contrast of only $\Delta n = 0.07$ between different regions of the structure is needed, as opposed to an index contrast of $\Delta n = 0.30$ for the step-index design. Furthermore, we can examine the ratio of the main lobe intensity to that of the side lobes. A higher ratio indicates higher contrast, which may improve photolithography applications. For the GRIN device, this ratio is 5.38, while the ratio for the step-index device is 4.24.

5. Conclusions

An extension of the step-index microsphere PNJ generator has been demonstrated. The proposed GRIN design produces a PNJ with a higher intensity hot spot without using high index materials. An intensity 45.3 times that of the incident wave is produced from a dielectric microcylinder composed of materials of index 1.7 of lower. The higher contrast between the intensity of the main and side lobes of the GRIN PNJ may allow for higher resolution photolithography.

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References


Dielectric Microstructures for Extended Photonic Nanojet Generation

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Abstract

The functional aluminum oxide microstructures of various geometry for the generation of extended photonic nanojets in transmission, as well as in reflection modes, were developed. The numerically calculated parameters of photonic nanojets are in good agreement with the experimentally obtained ones. The preliminary studies of the photoluminescence enhancement of sensitive layers under excitation by photonic nanojets revealed up to four-time an increase in its emission intensity.

1. Introduction

The development of new functional photonic materials and structures is an important interdisciplinary scientific problem. Its solution will contribute to the improvement of many advanced technologies, such as optical computing, new optical converters (including solar cells), ultra-high resolution optical microscopy, and sensor elements for highly sensitive registration of chemical compounds in liquid and gas media, as well as photocatalytic systems of various kinds.

One of the ways to increase the efficiency of the radiation interaction with media is the extended localization of light by microparticles of certain sizes – a phenomenon called a “photonic nanojet” (PNJ) [1]. During the last several years, there is considerable growth in the number of publications related to experimental demonstration and application of photonic nanojets. Currently, most studies of the PNJs are aimed at obtaining sharp focused high-intensity regions of radiation localization, which can be an alternative to plasmonic structures for super-resolution optical microscopy (so-called nanoscopy [2]), nanophotolithography [3], and Raman signal enhancement [4]. On the other hand, the considerable length of the photonic nanojet (up to several tens of wavelengths) can compensate for the relatively low intensity of its localization (comparing with plasmonic structures), making it promising to use this phenomenon for efficient excitation of optically active media of luminescent sensors and photocatalysts [5].

Reaching the limit of detection of chemical compounds in the environment at the ppb level (one part per billion) directly depends on two factors: (I) the possibility of recording of the interaction of a single analyte molecule with a chemosensitive receptor, and (II) the simultaneous excitation of a sufficient number of chemosensitive receptors to increase the probability of the reaction of an analyte molecule with one of them. The problem of increasing the efficiency of photocatalysts is similar: the greatest efficiency of the photodegradation of organic compounds or the enhancement of a chemical reaction will be achieved with maximum contact of the working medium with the surface of the photocatalyst. This implies the use of various kinds of porous structures although only their surface is well irradiated, and the rest of the photocatalytic material is illuminated only by scattered light. In this regard, localization of the exciting radiation into the volume of the photocatalytic structure using extended photonic nanojets will increase its productivity. Moreover, the potential applications of extended photonic nanojets can be expanded to excite photovoltaic elements and optical microscopy of thick biological sections and layers.

One should note that the reflective PNJ is affected by two main factors [6]: (i) the reflection from the substrate due to refractive index contrast and (ii) specific size-effect-induced light diffraction, as well as a mixing of the evanescent and propagating components of the incident and refracted radiation. These effects could be overcome by, for instance, applying a special anti-reflection coating or placing the microstructure at a certain gap from the substrate to control the modulation [7].

Here we demonstrate the experimental realization of a functional array of aluminum oxide microparticles of various geometry embedded in an optically sensitive layer generating the extended (not less than 2λ) photonic nanojets in both transmission and reflection modes promising for optical sensing purposes.

2. Materials and Methods

The preliminary numerical simulations of the microparticles geometry and PNJ parameters were performed by the finite difference time domain method. The fabrication of the ordered arrays of aluminum oxide microparticles (hemispheres or truncated cones) with pre-calculated geometric parameters was carried out by the combination of electron beam lithography, vacuum deposition, and selective chemical etching [5]. For experimental studies of PNJ propagation in an optically active medium, the fabricated microstructures were spin-coated with a chitosan polymer layer containing luminescent chemosensitive complex Eu(DBm)₃ (in the case of truncated cones) or rhodamine 6G dye (for hemispheres).
The refractive indices of PMMA, aluminum oxide, silicon, and chitosan are 1.495, 1.7731, 4.22469, and 1.545 respectively, at the incident wavelength of $\lambda = 532$ nm. The experimental studies of the photoluminescence enhancement of the sensitive layer under PNJ excitation were performed using a special home-build optical microscope set-up [5].

3. Results and Discussion

The photonic structures formed by the 200x200 μm ordered array of aluminum oxide truncated cones (top and bottom diameters are 1.6 and 2 μm, respectively; height is 0.7 μm) or hemispheres (diameter of 2 μm) coated by optically active layer were fabricated. The results of numerical simulations of the PNJs in transmission and reflection modes generated by the microstructures are presented in Fig. 1. The photonic nanojet formed by the truncated cones has two localization maxima of similar intensity but a different extension. The main calculated parameters of this PNJ in transmission mode, namely, the effective length, the FWHM, and quality factor are equal to 11λ, 0.3λ, and 464, respectively (Fig. 1a). In turn, the parameters [7] of the reflective photonic nanojet are the follows: the effective length is 4λ, the FWHM of 0.7λ, and the quality factor is 14.2 (Fig. 1b). In both cases, the PNJs are quite extended and their localization maxima are located outside the parental microstructures. The experimental images registered along the z-axis verify the propagation of both types of PNJs through the optically sensitive layer. When the structure is irradiated from the substrate, each microparticle generated an extended PNJ that locally excited the optically active layer.

![Figure 1](image)

Figure 1: (a) Numerical simulation and experimental image of PNJ in transmission mode generated by aluminum oxide truncated cones in Eu(Dbm)$_3$ layer; (b) Numerical simulation and experimental image of PNJ in reflection mode generated by aluminum oxide hemispheres in rhodamine 6G layer. The positions of the aluminum oxide microstructures are marked by gray dashed lines.

It is important to note that due to the low spatial coherency of excitation light source the modulation of the reflective PNJs by a standing wave was minimized. The photoluminescence enhancement factor was determined as a ratio between emission intensity in the PNJ maximum to the signal from the bare sensitive layer (the background or the area without PNJ). In the case of Eu(Dbm)$_3$, complexes excited by PNJs in transmission mode generated by truncated cones the enhancement factor was equal to 4. The reflective PNJs generated by hemispheres revealed a 3-fold increase.

4. Conclusions

Thus, the ordered arrays of alumina oxide microparticles generating the extended (up to 11λ) photonic nanojets both in transmission and reflection modes were designed and fabricated. The at least three-fold increase in photoluminescence intensity of the sensitive layers was revealed. That provides a great potential for further use of the proposed microstructures as a functional material for luminescent optical sensors, as well as photocatalysts.

Acknowledgements

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References


Plasmonics for single molecule detection and manipulation
Protein-Tailored Plasmonic Silver Nanorings over Graphene-Coated Nanopores for Localized Enhanced Fluorescence

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Abstract
Engineering electromagnetic fields through plasmons provides advances in several applications. Nanodevices with improved optical properties, for instance, are obtained using the architecture of proteins and their affinity towards nanomaterials. Here, silver nanorings are synthesized on the ring protein Prx and arranged over graphene-coated nanohole arrays achieving improved and localized fluorescence. This approach represents a proof-of-concept for future nanopore-based technologies, e.g. next-generation sequencing and single-molecule detection.

1. Introduction
Metal nanostructures are deeply investigated for their uncommon properties suitable in many applications including DNA sequencing [1]. For instance, their ability to couple with electromagnetic radiation and generate surface plasmons allows engineering and localization of electromagnetic fields which in turn can be exploited practically [2]. Though thin-film deposition and nanolithography represent forefront nanofabrication techniques, the alternative “bottom-up” approach is quickly emerging as a valuable and cost-efficient strategy. In this context, proteins are considered effective supramolecular tools to achieve design of novel functional nanomaterials. Proteins, indeed, are endowed with many anchoring sites suitable for crosslinking with dyes, other biomolecules or nanomaterials and exhibit different shapes and sizes useful to drive synthesis and assembly of nanostructures [3]. Here we show localized enhanced fluorescence on plasmonic nanopores through bio-assisted synthesis of silver nanorings (AgNRs) using the ring protein Prx. Prx self-assembles into a ring-like complex with thickness, outer and inner diameters of 4.5, 13, and 6 nm, respectively [4]. Moreover, the AgNRs can be tidily arranged over graphene-coated arrays of nanoholes taking advantage of the affinity of Prx towards graphene. We demonstrate that these hybrid structures can be easily produced as colloidal suspension and integrated on-chip to prepare arrays of functional plasmonic nanostructures [5]. These hybrid systems might have impact on nanopore-based technologies, i.e. single-molecule detection and next-generation sequencing where nanopore sizes comparable to the size of the genomic and proteomic information are highly demanded.

2. Methods and Results
2.1. Prx-Templated Synthesis of AgNRs
Wet synthesis of colloidal AgNRs was achieved by mixing Prx and AgNO3 in citrate buffer pH 5.5 at molar ratio 1.25 Ag+:1 Prx before chemical reduction with NaBH4 yielding small nanorings with diameter and inner pore of 28±3 and 3.0±1.3 nm, respectively, as demonstrated by TEM (Fig. 1A). The success of the strategy was assed by EDS showing elemental maps including sulfur unequivocally belonging to Prx and silver due to the presence of the synthesized metal (Fig. 1B). The citrate buffer was mandatory for 1) stabilizing the Prx in the ring-like conformation and 2) increasing the adsorption of Ag+ over the protein surface likely due to the negative charge of the citrate-coated protein.

Figure 1. A) TEM and B) EDS of Prx-templated AgNRs.

2.2. Prx-AgNRs Assembly on Solid-State Nanoholes
Taking advantage of the affinity of Prx towards graphene [6], the AgNRs were selectively arranged over a solid-state membrane with nanoholes. For this strategy, an array of nanoholes was obtained by means of focused ion beam
milling into a 100 nm thick Si$_3$N$_4$ membrane coated with 5/95 nm of Ti/Au. The final nanoholes were 60 nm large. The back side of the substrate was coated with gold, while Si$_3$N$_4$ was present at the front side. Plugging of the nanoholes was achieved by electrophoresis of exfoliated graphene flakes on the gold layer as reported previously for MoS$_2$ [7]. Prx has been labeled using a PEGylated Alexa647 dye before being deposited on the front side of the substrate. Then, the synthesis of AgNRs was carried out as described above to achieve the final hybrid nanostructure (Fig. 2).

![Figure 2. Final hybrid nanostructure including dye-labeled Prx-AgNRs deposited over the graphene-coated nanoholes.](image)

Drilling of graphene has been achieved by focusing electron beam resulting in 2 nm nanopores (Fig. 3A). Moreover, fluorescence confocal analysis demonstrated that in situ synthesis and deposition of the AgNRs successfully occurred along the whole arrays of nanoholes. The fluorescence properties of the dye were not affected by the synthesis procedure. Notably, intense fluorescence signals were recorded on both bare labeled Prx and labeled Prx-AgNRs demonstrating the pivotal role of the protein to act simultaneously as template for the synthesis, sticky items for localized deposition onto graphene and scaffold for functionalization with fluorophores. Indeed, in both cases the fluorescence was localized on the nanoholes resulting not altered after in situ synthesis of AgNRs (Fig. 3B).

![Figure 3. A) Drilling of 2 nm pores and B) confocal images of labeled Prx deposited over graphene-coated solid-state nanoholes before (left panel) and after (right panel) templated synthesis of AgNRs.](image)

### 2.3. Plasmonic Effect of PRX-AgNRs: Fluorescent Enhancement

The emission fluorescence enhancement over the hybrid nanoholes was measured by a home-made optical setup. For experiments, Prx and Prx-AgNRs were labeled with the ATTORho6G dye and deposited over the graphene-coated nanohole arrays. The measured fluorescence lifetimes of the samples were 2.3±0.4 and 1.0±0.8 ns for bare Prx and Prx-AgNRs, respectively, (Fig. 4) indicating that the fluorescence emission was two times more efficient over the hybrid Prx-AgNRs nanoholes. Such a lifetime reduction has been ascribed to surface plasmonic effects over the metal.

![Figure 4. Fluorescence lifetime of labeled Prx and labeled Prx-AgNRs deposited over the graphene-coated nanoholes.](image)

### 3. Discussion and Conclusions

The results provide a proof-of-concept to build devices with plasmonic 2 nm nanopores with enhanced fluorescence that could enable flow-through of molecules such as single strand DNA (1 nm) or small globular proteins (2 nm) [8]. For instance, the device potentially allows enhancement of signals from molecules flowing through the nanopore. This represents one of the first examples of hybrid plasmonic nanopores integrated on a 2D-material membrane. We foresee that the size and single-atom thickness of the device makes it suitable for advanced technologies such as next-generation sequencing and single-molecule detection.

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### References

Time- and Field-Resolved Response of Plasmonic Nanostructures and Their Applications to Single-Molecule Detection and Manipulation

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Abstract

Plasmonics exploits the collective motion of conduction electrons in metals (plasmons), thus enabling light to couple with nanoscale objects, with the consequent generation of a plenty of novel and unexpected optical effects and functionalities. Plasmonic nanostructures have been deeply studied in the last decade due to their crucial impact on several areas of nanoscience and nanotechnology. Their unrivalled capability to squeeze light well beyond its diffraction limit, leading to extremely confined and enhanced electromagnetic fields on the nanoscale at optical frequencies, is of great interest for the prospect of real-life applications, such as energy harvesting and photovoltaics, wave-guiding and lasing, optoelectronics, fluorescence emission enhancement, plasmon-assisted bio-interfaces and nanomedicine. In this framework, traditional studies of the resonant behavior of plasmonic nanoantennas rely on standard intensity detection schemes. Up to date, the temporal dynamics of plasmonic nanoantennas remains challenging. In the first part of the talk we will show that, by combining femtosecond time-domain spectroscopy and high-resolution confocal microscopy, it is possible to measure full time- and field-resolved response of single plasmonic nanoantennas [1]. In the second part of the talk, we will then show practical applications of plasmonic nanoantennas to single-molecule detection [2-4], enhanced spectroscopy on single-cells [5-7], optical trapping and nanoparticles beaming [8], enhanced Raman scattering [9-10] and resonant energy transfer [12] towards sequencing applications [13].

References

Toward investigation of reactive intermediates via Surface-enhanced Raman Spectroscopy (SERS)

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Abstract
The Surface-enhanced Raman Spectroscopy (SERS) and self-assembly approach have been used to investigate the possibility of aryl monoradicals generation from thiophenols and phenylmethanethiols substituted with iodine or bromine atoms. The monolayers of radical precursors were deposited on SERS substrates, which were then immersed in methanol and irradiated for six hours with a UVC lamp. Pre- and post-reaction SERS spectra were obtained by using a portable Raman spectrometer and compared with the spectra of expected products of reactions with methanol.

1. Introduction
Reactive intermediates with unpaired electrons, such as phenyl radicals, play an important role in organic synthesis and development of new biologically active organic compounds. However, experimental studies on them are difficult to carry out due to their high reactivity. The direct observation of the intermediates is not straightforward and requires application of advanced spectroscopic or spectrometric methods. Some examples of experimental studies on reactive intermediates include, the structural characterization of organic radicals by using IR spectroscopy in low-temperature matrices [1] and the reactivity studies on various mono- and polyradicals in the gas-phase by using Fourier Transform Ion Cyclotron Resonance (FT-ICR) Mass Spectrometry [2].

In order to study reactive intermediates, one has to be able to generate them from appropriate precursors and prevent their reactions for at least short period of time, i.e. by trapping them in low-temperature matrices or gas-phase. Only then it is possible to acquire i.e. their vibrational spectra or study their reactivities in controlled manner.

The surface-enhanced Raman spectroscopy (SERS) have a great potential for studying reactive intermediates. In SERS, the self-assembly approach can be used to deposit monolayers of analyte, i.e. reactive intermediates precursors, on SERS substrate. In such monolayers, the precursor molecules are separated from each other and therefore in certain conditions, under vacuum or in the inert gas atmosphere, the reactions of generated intermediates with each other or with molecules from surrounding environment will be prevented. One can also generate reactive intermediates in a selected medium (solvent) to study by SERS the products of their reactions.

The critical aspect in the reactive intermediates studies is their generation. Therefore the goal of our studies was to investigate by using SERS technique whether it is possible to generate reactive intermediates, organic monoradicals, from their precursors deposited on the SERS substrate.

2. Experimental section
1 mM solutions of thiophenol (PhSH) (Sigma Aldrich), benzyl mercaptan (BeSH) (Acros Organics), p-bromo thiophenol (PhSHBr) (Sigma Aldrich), p-iodothiophenol (PhSHJ) (Enamine) and (4-iodophenyl)methanethiol (BeSHJ) (Enamine) were prepared by their dissolution in ethanol. The SERS substrates, GaN-Au [3], were placed in Petri dishes with 3.5 cm diameter and covered by 2mL of ethanolic solution for 1 hour. In the next step they were washed with ethanol and dried. Next, they were immersed in methanol, which had been deoxygenated by sonification, and irradiated by UVC lamp (254 nm) for 6 h. After irradiation, the SERS substrates were dried and investigated via Surface-Enhanced Raman Spectroscopy. SERS spectra of PhSH, BeSH, as well as PhSHBr, PhSHJ, BeSHJ and products of their irradiation were acquired by using B&K TEK iRaman Plus spectrometer were measured in the range of 300-1800 cm⁻¹, with 785 nm excitation wavelength (30 mW). Spectra were measured 8 times with 2000 ms accumulation time.

3. Discussion
To generate organic monoradicals, the internal energy of their precursors molecules has to be increased to such a level when the activation energy exceeds the weakest bond dissociation threshold. Therefore for our studies we have used thiophenols and phenylmethanethiols substituted with iodine and bromine, two halogens forming weak bonds with aromatic carbon. It is known that in such type of aromatic compounds the C-X bond can be homolytically broken by irradiation with UV light [4]. In our studies, the SERS substrates with radical precursors deposited on their surface via self-assembly approach were irradiated with UVC light (Figure 1).
In general, the excitation energy of molecules, i.e. excited by irradiation, can be dissipated in various competitive photophysical and photochemical processes. In case of investigated system, we are not dealing with fluorophores, however excitation energy of molecule adsorbed on SERS substrates can be dissipated by energy transfer from precursor molecules to metal. This is a reason why we not only investigated bromo- and iodo-substituted precursors to check effect of C-X bond energy on radical generation efficiency, but also we used precursors with halogen-substituted aromatic ring separated from metal either by S atom or S-CH₂-group. Finally, in our experiments the SERS substrates with deposited radical precursors were immersed during irradiation in methanol. The monoradicals generated during irradiation are expected to react with methanol exclusively via H-atom abstraction [4]. Therefore, we have acquired first SERS spectra of thiophenol and benzyl mercaptan deposited on SERS substrates, which were in a good accordance with those published in literature [5]. The SERS spectra of PhSHBr, PhSHJ and BeSHJ deposited on SERS substrates were acquired before and after 6 hours of irradiation under UVC light. After irradiation, we have not observed changes in the SERS spectra of either PhSHBr or PhSHB samples, compared to samples before irradiation (Figure 2). In case of BeSHJ, we have observed in the spectrum additional bands corresponding to BeSH. This indicates that monoradical was generated during irradiation of BeSHJ deposited on SERS substrate.

In conclusion, we have shown in our preliminary studies that in used experimental conditions we were able to generate organic monoradical on SERS substrate. The structure of the radical precursor plays important role since only one precursor used in these studies has yielded radical. However, this only indicates that energy transfer between precursor molecule and metal surface influences the efficiency of the radical generation.

We can also conclude that 6h long exposure of radical precursors to UV light is insufficient for full conversion of investigated precursors to radicals. According to the literature [6-8], the radicals generation in solution have been carried out for 20-24 hours. Therefore, longer generation times will be used in the future. In addition, since the energy of aromatic C-NO₂ bond is similar to energy of C-J bond, the NO₂-substituted thiophenols and phenylmethanethiols will also be investigated.

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References

Structural Color for Displays and Imaging
Anticounterfeiting visible metaholograms multiplexed with spin, direction and wavelength

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Computer-generated holography (CHG) involves iterative numerical algorithms to obtain the phase and/or amplitude profiles needed to physically realize holograms. Metasurfaces consist of arrays of subwavelength nanoresonators that can control the wavefront of light in a desired way. They recently proved themselves to be an effective platform for CGH by surpassing the quality of traditional holograms in terms of image resolution and field-of-view. These metasurface holograms showed prospects not only in imaging and display but also in security applications [1]. In particular, applying metaholograms to anticounterfeiting applications requires not only the technology of encoding multiple pieces of information, but also the manufacturability of highly efficient devices. To meet these complex needs, we have implemented a highly efficient metahologram based on hydrogenated amorphous silicon (a-Si:H). Based on the a-Si:H, previously we demonstrated a reflection-type image hologram that can render holographic image under natural light such as flash light of cellphone or even under the sunlight, which is applicable in the anticounterfeiting applications as form of hologram security tags. [2]

In this abstract, I will discuss our efforts in realizing multifunctional a-Si:H metaholograms that can encode multiple pieces of information in a monolayer device for anticounterfeiting applications. First, I will present a spin-multiplexed visible metahologram [3]. A straightforward method for encoding multiple pieces of information in a single metahologram device is using polarization. To obtain significant birefringence for the control and reversal of photon spin, two sets of nanorods are designed, and depending on their orientation, they imprint inversed spin photons along their corresponding geometrical phase. As a result, this allows switching between two different images by simply flipping the handedness of the circularly polarized light on the transmission-type metahologram with 61% diffraction efficiency. Second, I will introduce a direction-multiplexed visible metahologram [4]. This approach is to multiplex two distinct pieces of information onto a monolayer metahologram operating in the forward and backward directions depending on the direction of light incident on the device. Particularly, in this part we will reveal underlying physics of high transmission efficiency (around 75%), which is the antiferromagnetic resonances in the a-Si:H nanorod. Finally, I will propose a wavelength-multiplexed switchable metahologram operating at visible and invisible domain [5]. The device consists of a-Si:H and gold (Au) metasurfaces in a monolayer device, which is fabricated by the electron beam lithography overlay process. The a-Si:H metasurfaces generate a visible hologram and the Au metasurfaces produce a NIR hologram simultaneously with low crosstalk. I believe our efforts for making a multiplexed metahologram will lead to pragmatic anticounterfeiting applications.

[4] I. Kim* et al., Nanoscale Horizons 5, 57-64 (2020) [Cover paper]
Dynamic plasmonic nanorod pixels

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Abstract

Plasmonic metamaterials present a new paradigm for color generation, but their properties are often either static in time or suffer from slow switching speeds. However, by reversibly aligning colloidal plasmonic nanorods using electric fields, we demonstrate rapid modulation of light on microsecond time scales. Tailoring nanorod aspect ratio and composition facilitates operation across the visible through short-wave infrared spectra. We characterize plasmonic nanorod pixels’ chromaticity and luminance, and showcase spatial, spectral, and temporal control of light in exemplary display devices.

1. Introduction

A great diversity of materials and designs have established plasmonic color generation as a vibrant area of research [1]. Many approaches present structured surfaces that, once patterned, remain fixed over time. To enable dynamic applications, these surfaces must often be coupled with a secondary active layer, such as liquid crystals, to modulate the optical properties. They are then constrained by the inherent switching speed limitations of conventional liquid crystal materials. As an alternative, we recently proposed the rapid alignment of plasmonic nanorods (NRs) in relatively dilute liquid suspensions as an emerging candidate for high-speed optical devices [2]. The NR plasmonic pixels modulate light on microsecond time scales [3], and can be designed to work across the visible and infrared spectra [4].

2. Results and Discussion

Metal NRs exhibit localized surface plasmon (SP) resonances associated with electron oscillations along their longitudinal (LSP) and transverse (TSP) axes. Figure 1 illustrates that a suspension of randomly oriented NRs will therefore absorb light at two wavelengths. However, purposely aligning the NRs’ long axes along the direction of light propagation suppresses the LSP, significantly modifying the spectrum. Here, the NRs are aligned in organic solvents by applying an alternating current (AC) electric field (magnitude 0–6 V/µm, 60 Hz or 5 kHz) across transparent conducting electrodes.

We design the NRs to operate at desired wavelengths by tailoring their aspect ratio and composition. Elongating the NR dimensions red-shifts the LSP resonance from ~600 through 2200 nm (Figure 2). To access shorter wavelengths, we show that the resonance can be blue-shifted by overcoating the Au NRs with Ag (followed by encapsulation in SiO₂ and alkyl-silane functionalization, denoted "Au@Ag@SiO₂@OTMOS").

Figure 1: (a) Schematic depiction of the dynamic plasmonic pixel when the applied electric field is OFF (unaligned) and ON (aligned). (b) Measured pixel extinction spectra of a suspension of aligned and unaligned Au NRs in toluene.
By appropriate choice and combination of NRs, light over a range of colors can be displayed and modulated, shown by color photographs (Figure 3a) and by mapping to chromaticity and luminance coordinates (Figure 3b,c). As the NRs align, more red light is transmitted, shifting the chromaticity and increasing the luminance.

Ease of integration into optical devices is highlighted by fabrication of a seven-segment numerical indicator (Figure 3d). By controllably regulating the passage of light at one or more specified wavelengths, the plasmonic pixel architecture is also well suited for high-contrast light valves and adaptive filters.

3. Conclusions

By demonstrating dynamic plasmonic pixels operating throughout the visible and infrared spectra, we highlight the versatility of plasmonic NRs for high-speed optical applications. We design NRs with a range of visible light chromaticities suited for color displays. Our fabrication of a plasmonic NR seven-segment indicator showcases that the NR materials are readily integrated into functional devices. We envision the plasmonic NR pixel not only in display applications but also as a generic spatial light modulation platform for arbitrarily controlling the phase, amplitude, and polarization of light on a relatively fast time scale.

Acknowledgements

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References


Figure 2: (a–c) TEM images of Au NRs with three different aspect ratios. (d) Measured normalized extinction spectra of eight different aspect ratio Au NRs as the applied electric field is varied from 0 V/μm (unaligned: thick black) to 6 V/μm (fully aligned: thick blue).

Figure 3: (a) Color photographs of the indicated NR suspensions (illuminated from the back by white light) when an applied 60 Hz AC electric field is either OFF or ON. The properties of the Au NRs are labeled as “diameter–LSP” (nm): that is, “25–650” and “25–600.” (b) CIE 1931 x,y chromaticity coordinates and (c) luminance values (Y) plotted as a function of applied electric field. (d) Composite of photographs of a fabricated seven-segment numerical indicator containing polystyrene-thiol-coated Au NRs in toluene. The indicator displays the numerals 0–9 as a 5 kHz electric field is applied across appropriate combinations of individually addressable, patterned electrodes. The outer dimensions of the “0” are 12.5 × 22 mm.
Structural Blue: Journey from fundamental research to real-life application as first omnidirectional structural color pigment

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Brilliancy and vivid appearance of structural colors seen in nature (e.g. fishes, insects and birds etc.) is attributed to higher reflectivity at narrow spectral bandwidths originated from combination optical interference and scattering of light through complicated structures. Significant research has been conducted to understand mechanism of these color generation in nature. Several groups’ also explored routes to replicate such colors in the laboratory in the form of periodic multilayer stacks, regular array of spheres, and disordered scattering media over several decades. Some also reported possibility of retaining angle independent response or ‘omnidirectionality’ with rather complicated optical films. In this talk we will discuss optical design strategies based on multilayer stack of thin-films to maintain brilliancy, omnidirectional characteristics of structural colors as well as feasible production methods for commercialization. This work paves the way to access of durable naturally brilliant and high chroma colors to automotive market and beyond.
High-purity hybrid structural colors by enhancing optical absorption of organic dyes in resonant cavity

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Abstract:
Structural colors, as alternatives to conventional organic dyes or pigments, have attracted considerable attention owing to their great promise in diverse applications, such as optical decorations, colored display/imaging, and optical detections. To date, various systems and different materials have been employed to produce wide-gamut structural colors utilizing plasmon resonance, Mie resonance, guided-mode resonance or Fabry-Pérot (F-P) cavity resonance. Compared with other color filters based on sub-wavelength nanostructures, lithography-free thin-film structural colors based on F-P cavity resonance hold greater potential toward their mass production and large-area applications. However, the existing thin-film reflective colors greatly suffer from the poor color purity due to the inadequate absorption outside the targeted color range.

In this work, we proposed a new and general method of incorporating an ultrathin organic dye film having the same color as the targeted color into a classic dielectric-absorber-dielectric-metal (DADM) film structure to achieve vivid, highly saturated reflective colors. After the organic dye layer is integrated into the F-P resonator, its intrinsic low absorption in the desired color range and high absorption at complementary color wavelengths are amplified by the excited cavity resonances, resulting in the high reflection of final color with significantly improved color purity. Besides, the fabricated device exhibits an excellent color stability in the accelerated UV exposure test due to the significantly reduced UV absorption of the dye layer, indicating the extended lifetime of the dye layer when integrated into the F-P resonator. Compared to previous approaches, the strategy proposed here largely simplified the design process of high-purity structural colors by avoiding the need and complexity of searching for the ideal absorbing materials, thereby opening up new revenues for wide applications of structural colors.

References


Short abstract
We present a simple and new method of incorporating an ultrathin dye film into a planar thin-film structure to realize high-purity reflective colors with drastically increased lifetime.
Plasmonic Electronic Paper

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Abstract
We work on developing reflective displays (electronic paper) in color by combining plasmonic nanostructures and electrochromic materials. The main motivation is to save energy in comparison with emissive displays.

1. Introduction

Our modern society has become entirely dependent on electronic displays for entertainment and for instant communication of information worldwide. Practically all displays are emissive and their energy consumption has become considerable. There is no obvious way to decrease the power use associated with emissive displays since they are already highly efficient at converting electricity to light (~30% for LEDs). The only solution is to develop displays that simply reflect the light from the environment, also known as electronic paper technologies. The most common electronic paper devices are electrophoretic displays (Amazon KindleTM). They are known to provide excellent visibility in bright conditions combined with extremely low power consumption.

However, it has proven very challenging to create electronic paper in color with good image quality.[1] One option is to simply introduce glass filters to generate subpixels, but this puts extremely high demands on brightness (absolute reflectivity) and contrast (change in reflectivity between on and off states). For instance, it is fully possible to create a reflective LCD color display, but with drastic loss in reflectivity due to the polarizers which immediately remove half of the incident intensity from ambient light.

In our work we try to create electrochromic pixels that provide high brightness and contrast. We use a combination of plasmonic structural colors and electrochromic materials that switch from transparent to broadly absorbing. This makes it possible to modulate the reflected colors in electrochemical cells. Both organic and inorganic electrochromism can be utilized and each option offers certain advantages. In this contribution I will present our latest results.

2. Results

2.1. Metasurfaces

Metasurfaces with high polarization-insensitive reflectivity are prepared over large areas by thin film deposition and colloidal lithography. In most cases we use an Al mirror, an Al2O3 spacer and a semi-transparent Au film with nanoholes. This structure can provide all primary colors by varying the Al2O3 spacer thickness.[2] The colors originate from a combination of a Fabry-Pérot cavity resonance and surface plasmons excited by the nanohole array.[3] The ultrathin structures are flexible (Fig. 1).

Figure 1: Metasurfaces with different colors. Reproduced from reference.[2]

2.2. Electrochromism

In order to switch the colors on and off we implement electrochromic films on top of the nanostructures. We recently compared the performance, especially in terms of contrast, of organic and inorganic materials (Fig. 2).
Figure 2: Switching primary colored metasurfaces (RGB). The spectra show the reflectivity change in devices with optimized contrast. (Submitted for publication.)

2.3. Pixel control

We have reproduced color images with metasurface pixels to test visual appearance. RGB stripes were prepared in different lengths (Fig. 3) We are currently working on addressing individual pixels in an active matrix. Preliminary results will be presented.

Figure 3: Picasso painting reproduced with plasmonic metasurfaces containing Al and Cu.[3] The image is approximately 5×4 cm². (Unpublished work.)

3. Discussion

In terms of brightness and contrast, the metasurfaces can outperform existing technologies for electronic paper using color filters.

4. Conclusions

We have developed a technology for reflective color displays with good image quality. The plasmonic electronic paper, just like other reflective displays technologies, will not outperform emissive displays in terms of brightness and contrast. However, it can operate with essentially zero power consumption and still generate reasonable image quality for many applications. This can lead to considerable energy savings in the future.

Acknowledgements

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References


Redox-tunable structural colouration by UV-patterned conducting polymer nanofilms on metal surfaces

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In this presentation, I will introduce our latest studies on the redox state tunable structural colouration based on conducting polymers and the use of UV-patterning technique for fabricating multi-colour images within single steps.

Precise manipulation of light-matter interaction has enabled various strategies, including Fabry-Perot cavities, photonic crystals, and plasmonics, to produce vibrant and non-fading structural colours \cite{1-3}. However, most of these approaches rely on complicated and high-cost fabrication facilities (e.g., electron beam lithography), and the resulted coloured area and colour tunability are limited. Herein, we proposed that by utilizing a bilayer device of conducting polymer film on metal mirrors could provide vivid structural colours \cite{4}. The UV-patterning treatment during the polymer deposition enables the synergistic modulation of polymer permittivity and film thickness, leading to the finally obtained reflective colours. By utilizing greyscale photomasks, this technique can convert greyness into various colours, and multi-colour images were fabricated successfully within single steps. The obtained colours can further be tuned by the redox states of the conducting polymer with high precision. We believe this new proof-of-concept device and the UV-patterning method could be promising for the future smart displays.

References

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Controllable generation of large-scale highly-regular gratings for structural coloring applications

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Femtosecond laser-induced periodic surface texturing holds great potential applications in medicine, optics, tribology, biology, etc. However, when irradiating by a large intense laser spot, the periodic structures usually exhibit uncontrollable regularity, forming bifurcated patterns and thus limiting their widespread applications. The irregularity originates from numerous branching seeds that appear independently. The usual solution to this problem is utilizing the quasi-direct laser writing technique, that is, by limiting the laser beam size (diameter\textless10 wavelengths) and scanning the beam or samples by 2D translation stages. Here, we demonstrate an optical localization-induced nonlinear competition mechanism to solve this problem, which occurs at a fluence nearly one order of magnitude below the ablation threshold. Thanks to the low intrinsic absorption of silicon and the ultralow applied fluence, this mechanism ensures self-selection of a single seed to initiate an array of bifurcated-free grating under stationary irradiation with a large laser spot (diameter\textgtr100 wavelengths). More surprisingly, some unconventional complex patterns, such as radial, annular, and spiral gratings can also be easily produced by structured light fields with unprecedented regularity. Their diameters reach up to >500 wavelengths. Moreover, we are capable of artificially controlling the initial seeding structure to further improves the gratings’ regularity, defined by dispersion in the ripples’ orientation angle in their 2D Fourier transform. As a result, the regularity in our experiments produced by a large laser spot is even higher than that scanned by a tiny beam. The controllable and highly regular ripples are beneficial to the structural coloring effects, as they arise from the light diffraction by the subwavelength gratings.
Figure 1. SEM image (a) and its 2D fast Fourier transform (b) of femtosecond laser-induced regular ripples on a 200 nm thick a-Si thin film. The red arrows denote the laser polarization direction. High-resolution SEM image (c) and corresponding EDX map (d) of a representative LIPSS, which illustrate that the ripples arise from periodic surface oxidization. The periodicity of the ripples is measured to be ~950 nm. (e) In situ cross-sectional imaging of the ripples milled by a Ga⁺-based focused ion beam. (f) Optical microscopy image of a set of LIPSS that are produced by various laser polarization directions (arrows), forming a colorful element symbol of “Si”.

Bottom-up approaches and new fabrication routes
Self-assembled chiral plasmonic metasurfaces

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Abstract

Chiral plasmonic metasurfaces are self-assembled from oriented non-chiral metallic nanowires and nanorods using Grazing Incidence Spraying combined to the Layer-by-Layer assembly approach. The resulting thin films display a very high circular dichroism over the whole visible and near-infrared wavelength range, and the optical properties are highly dependent on the superstructure which can be easily tuned by this approach.

1. Introduction

Recently there has been great interest in developing metamaterials that can control the flow of electromagnetic waves in unprecedented ways. These metamaterials need to have subwavelength dimensions, i.e. in the range of tens of nm for optical applications, and have mostly been manufactured by top-down technologies that have the disadvantage of being quite expensive and slow. Obtaining large areas and regular (3D) ordering is difficult, and nanoparticle self-assembly appears to be a promising alternative. A big challenge, however, still resides in the hierarchical organization of these nanoscale building blocks into two- or three-dimensional structures with well-controlled location, orientation, and spacing across multiple length scales. In particular, chiral assemblies of plasmonic nanoparticles are proposed as an alternate route for the fabrication of optical metamaterials.[1]

2. Results and Discussion

2.1. Fabrication of chiral metasurfaces

Here, we use a novel technique, called Grazing Incidence Spraying (GIS), that we have developed for the self-assembly of silver nanowires and gold nanorods as mono- and multilayer thin films (Fig. 1a).[2-5] It allows aligning anisotropic nano-objects on large areas with tuneable particle density and orientation (Fig. 1b). The thin films are highly oriented (the 2D nematic order parameter can be as high as 0.9). Furthermore, GIS can be easily combined with the well-established Layer-by-Layer assembly technique,[6] and the orientation direction and composition of each layer can be chosen independently. Using this combined approach, helical (and thus chiral) multilayer thin films can be formed easily over large areas (Fig. 1c).

Figure 1: a) Scheme describing the Grazing Incidence Spraying (GIS) deposition technique, b) SEM picture of an oriented silver nanowire monolayer, c) scheme of chiral tri-layer samples, in which the director is rotated 60° between each layer, and d) CD spectra, showing plasmon-induced CD peaks of very high intensity.

2.2. Optical properties

The oriented monolayers of plasmonic 1D nanoparticles display highly anisotropic optical properties, namely high linear dichroism and birefringence, as the transverse and longitudinal modes of the localized surface plasmon resonance can be excited selectively using linearly polarized light. Helical metasurfaces display a giant circular dichroism (Fig. 1d) and birefringence which arises from the chiral superstructure. Mueller Matrix Polarimetry shows that the optical properties are a complex combination of circular dichroism and birefringence and linear dichroism and birefringence.

The interest of our approach is that it allows building the metasurface step-by-step and each relevant structural parameter can be chosen at will (density, composition and
orientation of each layer, as well as the spacing between the plasmonic layers. The strong dependence between the optical properties and the superstructure can thus be unveiled.

3. Conclusion

The combination of GIS and LbL assembly allows forming chiral plasmonic metasurfaces at low cost over large areas. The thin films display chiroptical properties (in particular a giant CD) that strongly depend on the superstructure of the assembly.

References


Directed Assembly of Hybrid Colloids for Optics

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Abstract

Colloidal assemblies of gold nanoparticles were synthesized using an emulsion-based formulation route. The synthesis involved the emulsification followed by the controlled drying of an aqueous suspension of gold nanoparticles in an oil phase. The structural control of the as-synthesized clusters is demonstrated using different techniques. Their optical resonant properties are determined by spectroscopic polarized multi-angle light scattering. The study evidences strong optical magnetic dipolar resonances and strongly forward scattering patterns, both being tunable by the monitoring of the cluster inner structure.

1. Introduction

The manipulation of light propagation has been the subject of intense research efforts ever since ancient civilizations. These research efforts have been revived by the advent of nanotechnologies and nano fabrication methodologies. Nanophotonics then started to explore the possibility of modulating light propagation with very small amounts of matter using nanoscale phenomena like diffractive effects or nanostructure resonances [1]. The range of possible optical functions seems now to widen dramatically, while being accessible at sub-wavelength dimensions with the benefit of enabling miniaturized devices. Tailored composite resonances have been engineered in 2D lithographically-produced nanostructures [2, 3, 4], but also in isotropic colloidal meta-atoms consisting of either simple dielectric spheres [5, 6, 7] or assembled complex colloids [8, 9, 10, 11, 12, 13], with the additional benefit of giving access to bulk isotropic materials with \( \mu \neq 1 \) [14]. The interest for meta-atoms consisting of nanoparticles (NPs) clusters [9] has been revived recently. The design proposed by Dezert et al. [15] consists in an assembly of N NPs of radius \( r \) distributed quasi-homogeneously within the spherical volume of radius \( R \) of a so-called NP-cluster. The NP-clusters can then be described as effective medium spheres. The study shows that interesting properties are obtained if the constituting NPs are either plasmonic (metallic NPs) or of high refractive index (silicon or titanium dioxide for instance). In such cases indeed, the optical index of the effective medium constituting the sphere can be tailored by varying the cluster filling fraction \( f = N (r/R)^3 \). Dense clusters of NPs have been produced by different chemical and physico-chemical routes, using block copolymer self-assembly, hydrophobic interactions, smart polymer brush coverage, specific ligand association, or electrostatic assembly, for example. Not often do these methods provide a good control on the cluster size distribution. Confinement of nanoparticles in emulsion droplets has been considered as a powerful way to control their assembly either for a small [16] or for a large [17] number N of NPs in the cluster. In the former case, ordered clusters with a configuration defined by the Lennard-Jones cluster geometry (for \( N < 7 \) ) are formed. In the latter case, the NPs within the cluster may, under certain conditions, present crystalline order. Here we report on the use of the ripening of emulsion droplets containing plasmonic NPs for the fabrication of optical colloidal resonators. The talk first presents the chosen emulsion system, then the evolution and control of the colloidal structure along the ripening process, and finally the results of the study of the spectral and angular light scattering properties of the final clusters. They present odd scattering modes (magnetic dipole plus electric quadrupole) reaching an intensity significantly larger than other gold complex colloidal nano resonators studied so far.

2. Results and discussion

Citrate-coated 7nm radius gold NPs were first synthesized in water. Citrate was then replaced with a polymer, polyethylene glycol with a thiol group (PEG-SH), of varying molecular weight \( M_w = 800, 2000 \) and 6000 g/mol. The resultant solution was then emulsified at a concentration of 20 wt% in dodecane. The emulsion was then dried to evaporate the water, thus bringing the nanoparticles closer in order to obtain the final clusters. The morphology of the plasmonic clusters were studied using Cryo-Transmission Electron Microscopy (Cryo- TEM) as shown in Fig.1. The samples were prepared by freezing the colloidal suspension of NPs clusters in dodecane using liquid ethane. Their internal structure can cannot be fully resolved by TEM due to the large NP density, but it appears very regular, and the juxtaposition of images of the same object at different tilt angles show no evidence of large voids within the object.
The light scattering properties of the clusters in dodecane suspension were studied using a variable angle polarization resolved static light scattering setup. The light scattered by the clusters suspension in the forward (20°–90°) and the backward direction (90°–140°) was measured using a spectrophotometer. At an angle of 90°, the ratio of the intensities of odd (magnetic dipole plus electric quadrupole) to even (electric dipole plus magnetic quadrupole) modes reaches a resonant maximum between 0.2 and 0.7 for wavelengths close to 650 nm, showing the strong optical magnetism of the nanoresonators. As shown in the Fig. 2, the scattering efficiency strongly depends upon the wavelength and the scattering angle. The scattering is predominantly forward on the whole wavelength range, which can be related to a strong magnetic dipole mode. This behaviour is characteristic of what is known as a Huygens scatterer. The formed cluster strongly interacts with light and when deposited to create a meta-surface, can be used to control the phase of the optical wave.

3. Conclusions

We demonstrate that dense clusters of plasmonic NPs can be synthesized using a bottom up emulsion based formulation route. The as synthesized clusters behave as Huygens sources with a strong forward scattering in the visible spectrum range.

References

Optical Properties of Artificial Chiral Metasurfaces

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Abstract
Here we investigate optical chiral properties of metasurfaces fabricated by means of nanosphere lithography. This low-cost and simple technique combined with angled evaporation of a plasmonic layer was employed to produce arrays of tilted elliptical nanoholes in Au or Ag. The elliptical shape and the in-plane tilt lead to the symmetry breaking, which further enables different coupling with circularly polarized light of opposite handedness. We investigate intrinsic and extrinsic chiral behavior in the visible and near infrared range, and report on possibilities to use this approach for chiral sensing and chiral light manipulation at the nanoscale.

1. Introduction
When nanostructures realized on a substrate have spatial arrangement comparable or less than the light wavelength exciting them, we name them as metasurfaces. These artificial structures enable novel light coupling phenomena otherwise not found in natural materials. A great example are widely studied plasmonic arrays of nanoholes (NHA), which lead to phenomena such as surface plasmon polaritons (SPPs) and extraordinary light transmission (EOT). NHAs have already been proposed for applications spanning from biosensing to communications. Moreover, a low-cost nanosphere lightography (NSL) can be utilized to produce high quality NHA samples, with applications in sensing [1] or light emission control [2]. On the other hand, nowadays nanofabrication allows for another degree of freedom: a symmetry breaking. Namely, nanostructures and metasurfaces can be specially designed to mimic chirality, a lack of mirror symmetry which is an important property of many molecules, enzymes, drugs, DNA. The symmetry breaking can be induced during the fabrication, e.g. by covering a semiconductor nanomaterial with an asymmetric plasmonic layer [3,4]. Chiral nanomaterials enable enhancement of light-matter interaction at the nanoscale and have been proposed for coupling with chiral molecules [5].

Here we show yet another possibility enabled by low-cost fabrication and symmetry breaking: chiral effects in NHA metasurfaces. Recently, we showed that NSL can be combined with tilted metal deposition to produce extrinsic chirality in metasurfaces based on polystyrene nanospheres (PNS) asymmetrically covered by metal [4]. Moreover, we noted that a small in-plane tilt during the tilted metal deposition can lead to chirality even at normal incidence (intrinsic chirality). From the numerical simulations we noted that chiral properties remain even if PNS is removed, leaving on the substrate array of tilted elliptical nanoholes due to the shadows formed by PNS during the tilted metal deposition. We further proposed the PNS removal for the circular dichroism (CD) investigation in tilted elliptical nanoholes [6]. More recently, we spectrally characterized Ag NHA sample where the PNS were removed, thus leaving the elliptical NHA with triangular symmetry [7]. Here we report on the CD in extinction in the 680-1000 nm range in various samples based on NHA in Au. We investigate possibilities to control and enhance CD by samples in-plane rotation or by oblique incidence. We believe that such simple system can be further optimized to provide even higher CD in a desired wavelength range, and that the chiral molecules can be more easily coupled with it for enantioselectivity measurements.

2. Fabrication
A four-step process involving NSL and symmetry breaking [7] was employed to obtain Au-NHA chiral metasurfaces, starting from PNS (Microparticles GmbH) with diameter of 518 nm, self-assembled on a glass substrate. Fig. 1 shows the Scanning Electron Microscopy (SEM) image of the sample Au03 before (left) and after (right) the PNS removal.

Figure 1: SEM images (scale bar 200 nm) of Au chiral metasurface Au03 before (left) and after (right) PSN removal.
3. Experiment

We characterize CD by using a widely tunable near-infrared laser (Chameleon Ultra II by Coherent Inc.), with the pulse duration of the laser is 140 fs, and the repetition rate of 80 MHz. For linear characterization we use a mechanical chopper at 70 Hz. Before impinging on the sample, the power is decreased by a beam-splitter and a neutral density filters. A quarter wave-plate is put on the light path before the sample to form circularly polarized light, Fig. 2; the angles of its fast axis with respect to the y-direction are 0°, +45° and -45°, corresponding to linear polarization, right and left circular polarization (RCP and LCP), respectively. Insets of Fig. 2 show two types of experiments: CD and left circular polarization (+45° and -45°, respectively) to the y plane tilt moves the ellipse axis away from the lines of triangular symmetry. This intrinsic chirality provides non-zero CD signal at normal incidence, which can further be increased by the oblique incidence and the samples’ in-plane tilt. We believe that this approach can enable easier chiral light interactions at the nanoscale.

Insets of Fig. 2 show two types of experiments: CD dependence on incident angle $\theta$ with a fixed in-plane tilt $\phi$ (top), and CD dependence on $\phi$ at normal incidence (bottom).

First, we notice that for normal incidence, there are zones with lower, but non-negligible CD. This indicates that the sample is already at normal incidence intrinsically chiral. CD can be further enhanced in both signs by properly choosing $\theta$ and wavelength, which can be optimized for chiral sensing. Moreover, spectral features of the CD change follow the dispersion lines of SPPs excited with LCP or RCP, which could lead to another interesting topic of chirality and spin of the light coupled to SPPs.

4. Discussion

We measure the zeroth order transmission under LCP and RCP excitation and calculate extinction as $\text{Ext}_{\text{LCP}}=1-T_{0,\text{LCP}}$, and $\text{Ext}_{\text{RCP}}=1-T_{0,\text{RCP}}$. We further define the CD in extinction as: $\text{CD}=100\left(\text{Ext}_{\text{LCP}}-\text{Ext}_{\text{RCP}}\right)/\left(\text{Ext}_{\text{LCP}}+\text{Ext}_{\text{RCP}}\right)$, similar to the way we defined it in absorption [3]. In Fig. 3 we show result for the AuNHA sample Au03.

![Figure 2: Experimental set-up for CD characterization. Insets show measurements of CD($\theta$) at fixed $\phi$ (top), and CD($\phi$) at $\theta=0^\circ$.](image)

![Figure 3: CD($\theta$) for the chiral metasurface Au03.](image)

5. Conclusions

We report on novel way to design, fabricate and manipulate the chirality at the nanoscale by means of low-cost plasmonic nanohole based metasurfaces. The symmetry breaking enabling CD in these metasurfaces relies on two effects: first, oblique metal deposition leads to the elliptical shape of nanoholes (compared to the circular shape when the deposition is in the direction of the surface normal); second, the in-plane tilt moves the ellipse axis away from the lines of triangular symmetry. This intrinsic chirality provides non-zero CD signal at normal incidence, which can further be increased by the oblique incidence and the samples’ in-plane tilt. We believe that this approach can enable easier chiral light interactions at the nanoscale.

References

Combining top-down and bottom-up techniques to fabricate metamaterials

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Abstract
By combining top-down and bottom-up nanotechnologies, we fabricate an isotropic metamaterial with a resonant electric and magnetic response. Our approach is based on realizing a large number of nano-scatterers by fast character projection electron-beam lithography and their subsequent randomized embedded into a liquid matrix, which can later be applied to any other surface and solidified. Our approach unlocks novel opportunities to fabricate metamaterials with a complex optical response in the bulk but also on top of arbitrarily shaped optical elements.

Concept and results
To make the best out of the two worlds of bottom-up and top-down nanotechnologies, we introduce and demonstrate a fabrication route that merges both approaches. We start by fabricating with a high-speed and large-scale electron beam lithography process complicated but spatially quite homogenous strongly scattering meta-atoms on top of a thin sacrificial layer on a substrate. Here, we choose a metal-dielectric-metal meta-atom that sustains a strong electric and magnetic dipolar resonance. The initial layer stack comprised a fused silica substrate, a thin sacrificial layer, and a double layer of electron-beam resist (CSAR and ARP). The resist stack was exposed by electron beam lithography in cell projection mode with a circular pattern arranged in a square periodic fashion and afterward developed. Thereafter, subsequently Au, SiO₂, and Au were deposited. Finally, the residual material was removed by lift-off. The resulting meta-atoms were integrated into a membrane by spin-coating a thin layer of polyvinyl alcohol (PVA) in which they continue to be embedded after the sacrificial layer is selectively dissolved and thus releasing the membrane from the substrate. The membrane can be scrambled, to introduce the necessary disorder and densified to make a bulk material out of it that can be deposited at any desired surface. We chose a planar substrate and achieve with that a thick material layer that inherits its optical response from the individual meta-atoms. Thanks to the random arrangement and orientation of the meta-atoms, the optical response is isotropic. In our study, the transformation of a subwavelength nanostructured metasurface to a voluminous photonic nanomaterial is investigated from a morphological and optical point of view

Departing from a perfect periodically arranged nanostructure array, it is shown that the magnetic and electric dipole resonances of the meta-atoms are preserved even after transforming the metasurface into a voluminous photonic nanomaterial including a randomized orientation and arrangement of the meta-atoms. The work comprises all experimental aspects concerning the fabrication of the material and its characterization at the different stages. Full-wave optical simulations support the experimental results of the spectroscopic analysis. Excellent agreement between experiment and theory is found.

One key finding is, that, although operating in-plane, well-established nanolithography can be utilized to realize an optically functionalized voluminous photonic nanomaterial. The second key finding is the possible transformation of an optically anisotropic behavior inherently connected with the design of the individual meta-atom or with the arrangement in the metasurface, into an isotropic behavior making the optical response independent from the incident angle of light. In perspective the optically functionalized membrane on the one hand and the voluminous photonic nanomaterial on the other hand, can be spatially transferred onto any surface with the presented peel-off procedure. In conclusion, our work paves the way for a “photonic nanomaterial paint”, which can be applied to any functional optical surface.

References
Reversible strain-tuning of quantum optical emission in WSe$_2$ monolayers

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Abstract

The future development of ultra-compact two-dimensional (2D) photonic technologies for quantum information processing relies on our ability to tailor the optical properties of single photon sources in 2D nanomaterials. In this talk, we will present hybrid 2D-piezoelectric devices for the reversible manipulation of the emission energy of quantum emitters in wrinkled WSe$_2$ semiconductor monolayers. Our results show a record tuning range of about 15 meV while preserving a high single photon purity.

1. Introduction

The family of two-dimensional (2D) semiconductor transition metal dichalcogenides (TMDs), including WS$_2$, WSe$_2$, MoS$_2$, or MoSe$_2$, offers several advantages for optoelectronic and photonic applications. They feature a variety of properties such as direct bandgap when thinned down to the monolayer, quantum confinement due to their reduced out-of-plane dimensionality, large oscillator strength and quantum efficiency, optically controlled injection of electrons with defined spins for quantum spintronics and spin-photon interfacing.

Another major advantage of 2D materials compared to conventional semiconductors is their impressive “stretchability”, as they can withstand strain magnitudes well above 1% before mechanical rupture takes place. This offers a large playground for elastic strain engineering since externally applied strain -by direct bending or using piezoelectric actuators [1-3]- provides a natural strategy to tailor the electronic and optical properties of the material. The discovery of single photon emitters (SPEs) in 2D materials has stimulated an intensive research effort, aimed at the exploitation of such sources for quantum photonics as well as at the understanding of their physical origin. In the last years, SPEs have been reported on TMD monolayers at cryogenic temperatures [4] and on layered hexagonal boron nitride up to room temperature [5].

However, quantum emitters in 2D materials deliver photons at random energies, which are difficult to control owing to the complexity either of the potential profile eventually leading to the exciton confinement or to the nature of the point defects. In turn, this severely limits the suitability of 2D SPEs for applications in quantum information science and technology. Therefore, it is fundamental to develop post-fabrication tuning methods capable of controlling the SPEs emission energy in a reversible manner while leaving their optical quality unaffected. Elastic strain engineering of the material’s band structure is a promising strategy to accomplish this task.

In this work, we successfully demonstrate active tuning of the emission energy of SPEs in WSe$_2$ monolayers using hybrid 2D-piezoelectric actuators. We show that the emission energy can be tuned up to 18 meV for moderate applied electric fields of about 15 kV/cm preserving a high single photon purity [6]. The possibility of obtaining site-controlled and tunable quantum emitters will be discussed.

2. Discussion

Spectral control over one of the SPEs is demonstrated by
sweeping the electric field across the piezoelectric actuator from \( F_p = -20 \text{ kV/cm} \) to \( F_p = 20 \text{ kV/cm} \) as shown in Figure 2a. Specifically, an emission energy blue/red shift is observed for compressive/tensile strain fields introduced by the actuator, which is attributed to an increase/decrease of the bandgap in crystalline semiconductor materials. Moreover, the shift of the emission can be reversibly tuned in a linear fashion, as in principle expected for moderate magnitudes of the strain delivered by the piezo-actuator. From a linear fit to the measured spectra, we can infer a total energy shift of about 5.4 meV with a ratio 5.4 μeV/V, similar to the values reported in semiconductor nanomembranes containing quantum dots.

We investigate the influence of induced strain fields on the spectral shape and quality of the single photon emission as seen in Figure 1. Notably, we observe a well-pronounced anti-bunching signal at zero delay times \( (\tau = 0) \), allowing us to extract a deconvoluted \( g(2)(0) \) value of ~0.13 for an applied electric field \( F_p = -20 \text{ kV/cm} \) and ~0.12 at both positive and negative \( F_p = 20 \text{ kV/cm} \). From the single exponential decay of the correlation function carried out in the non-saturation regime of the exciton, we can furthermore estimate the spontaneous emission lifetime of the exciton with a value of about 1.0 ns. Importantly, both the exciton lifetime, as well as the single photon purity of the emitter are fully retained in the presence of mechanical stress, as evidenced by the comparative plot in Figure 1c. This unambiguously confirms that strain does not alter the quality of the single photons emitted by quantum emitters in 2D materials – at least for the strain magnitudes and anisotropy investigated in this work.

**Figure 2:** a, Contour plot of the μPL spectra of a SPE as a function of the applied electric field on the piezoelectric actuator. The observed red- and blue-shifts are due to the induced compressive and tensile strain fields by the actuator. An energy shift equal to 5.4 μeV/V is observed. b, PL spectra of the SPE in a) for zero and the maximum electric fields applied on the actuator (red and blue lines). A total shift of 5.4 meV is obtained for a total 40 kV/cm sweep. c, Second order auto-correlation \( g(2)(\tau) \) measurements of the dot in a) for \( F_p = 0, -20 \) and 20 kV/cm. The single photon emitter nature of the SPE is confirmed by the low deconvoluted value \( g(2)(0) = 0.13, 0.12 \) and 0.12, respectively, which is independent of the applied field (i.e. induced strain field). Extracted from Ref [6].

### 3. Conclusions

In summary, we have demonstrated active control of the energy emission of SPEs localized in a wrinkled WSe₂ monolayer. This is achieved developing a hybrid 2D-piezoelectric device where in-plane biaxial strain fields up to a magnitude of ~0.15% can be transferred to SPEs without degrading their optical quality. We demonstrate a record tunability up to 18 meV – much larger than the best reported values in 2D materials. Moreover, the SPEs retain a high-purity single photon emission upon the introduction of strain fields, as shown by time-correlation measurements. Finally, we have observed that different SPEs located in the same wrinkle shift to both higher and lower energies for the same applied stress. FEM simulations suggest that this peculiar behavior is related to the specific location of the SPEs and to the high non-uniform strain distribution across the wrinkle. The results reported in this work pave the way towards the exploitation of energy-tunable SPEs and emitters of entangled photon pairs based on two dimensional crystals and it will stimulate the use of strain-fields to understand the origin of SPEs in 2D materials.

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### References

Non-fading Plasmonic Color Printing through Laser Processing of Semicontinuous Metal Films

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Abstract

We report non-fading generation of vibrant colors through a femtosecond laser post-fabrication processing of a plasmonic semicontinuous metal film deposited on a metallic mirror coated with a sub-wavelength-thick dielectric spacer. Long term stability of color is obtained through structures’ overcoating with a dielectric layer. Local changes induced to nanostructures of semicontinuous film are controlled by the femtosecond laser parameters, especially fluence. Wide range of vibrant colors in reflection mode from blue to green, to red can be easily obtained.

1. Introduction

Semicontinuous metal films (SMF) are made of randomly distributed metallic nanoparticles. The SMFs are often formed at the initial stage of metallic layer deposition on a nonwetting surface \([1,2]\). When the SMF is irradiated with a laser beam, electromagnetic energy can concentrate in regions known as ‘hotspots’ \([3]\). Heat generated in this process can lead to reshaping and fragmentation of metallic nanostructures near the hotspot region. One can control the amount of induced changes, and thus spectrally selective modification of transmittance, reflectance and absorption spectra of the SMF, by adjusting laser parameters \([1,4]\).

Laser modification of SMFs and SMF deposited on a metallic mirror coated with a sub-wavelength dielectric spacer (we refer to such structure as SMF on mirror – SMF/M) has been recently used for generation of plasmonic colors \([2,4-7]\).

Here, we present our resent results on lithography-free, non-fading color printing through a femtosecond laser processing of dielectric layer coated plasmonic semicontinuous silver films deposited on a metallic mirror coated with a sub-wavelength-thick dielectric spacer. This technique is inexpensive and allows for high resolution and high throughput plasmonic color printing.

2. Results and discussion

We fabricated silver SMF/M using an electron-beam physical vapor deposition technique. As a mirror we used a 100 nm Ag film deposited on a glass substrate with a 5 nm Ti wetting layer. As a dielectric spacer we used 30 nm of silica. The thickness of Ag SMF layers was varied in the range of 3-20 nm. From our previous work \([2]\) we know that the top Ag film of SMF/M is not stable and that the reflectance of SMF/M changes in a matter of few days. Thus, we overcoated the SMF/M structures using a dielectric film. Two approaches were tested. First, in the same process of SMF/M deposition we overcoated the structure with 90 nm silica film. In the second approach, we used atomic layer deposition (ALD) technique. Freshly fabricated SMF/Ms were transferred to an ALD system and overcoated with a 5 nm thin alumina layer. Both approaches resulted in long term (several months) stability, but different colors of samples were observed.

We performed a series of laser post-fabrication processing tests on the overcoated SMF/Ms. We used an ultrafast Ti:Sapphire femtosecond laser (1 kHz, 80 fs, 800 nm, linear polarization). An in-house built laser scanning setup based on a computer-controlled motorized XYZ stage was used in order to uniformly modify a few millimeter square areas. In Figure 1 we present the reflectance spectra (measured with linearily polarized light co-polarized with respect to laser polarization) and the corresponding CIE 1931 color diagram of the different areas of a 5 nm alumina coated 7 nm Ag SMF/M photomodified with different laser fluence. The laser modification results in strong changes of the reflectance of the overcoated SMF/M. We observe a broad range of vibrant stable colors that can be further optimized to obtain a much broader color gamut. Similar effect was observed for the SMF/Ms overcoated with 90 nm silica film, however the color range was limited.

These unique plasmonic SMF/M structures, along with laser printing, can be utilized for plasmonic coloration and printing on almost any substrate (rigid/flexible). Therefore, our approach opens up the potential for vast research and real-life applications.
3. Conclusions

Post-fabrication laser processing of dielectric film coated plasmonic semicontinuous metal films deposited on metallic mirror with sub-wavelength thick dielectric spacer results in generation of vivid colors. Overcoating of the silver nanostructures with a few nanometers thick alumina film formed through atomic layer deposition or a hundred nanometers silica film results in long term, order of many months, stability. The presented technique is inexpensive and allows for high resolution and high throughput printing, thus could allow widespread use of plasmonic color generation in real life applications.

Acknowledgements

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References


Figure 1: Laser modification of 7 nm Ag SMF/M overcoated with 5nm alumina. (top). Reflectance spectra and (bottom) corresponding CIE 1931 color diagram of areas photomodified with different laser fluence measured with linearly polarized light co-polarized with respect to laser polarization. The inset squares represent the generated color palette recorded using unpolarized light.
Tunable hyperbolic metamaterials for wavefront shaping and fingerprint

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Abstract
In this work, we present a tunable multifunctional hyperbolic metamaterial composed of alternating layers of functionalized transparent conductive oxide (ITO) and insulating material (SiO2). Proposed plasmonic architecture allows to guide/squeeze and trapping the light at the nanoscale, which leads to a number of applications ranging from nanophotonic circuits to sensors. Furthermore, a novel sub-wavelength fingerprint recognition system was presented, which can be a milestone for real-time sensing/imaging applications.

1. Introduction

Hyperbolic metamaterials (HMMs) are one of the most promising topological photonic metamaterials capable to control/manipulate bosonic systems like surface-bulk plasmons, excitons, excitons-polaritons at the nanoscale [1,2]. The control of the topological shape of the isofrequency contour (IFC) allows unprecedented manipulation of photons, leading, in particular scenarios, to the occurrence of high k-modes (hyperbolic modes), guide/trapping the light and an increase in local or projection density of the states. Therefore, the HMMs reveal marvelous aspects that lead this class of metamaterials to execute a fundamental role in emerging applications, i.e.: single photon emission [3], ultrasensitive sensing [4], efficient modulators [5], photonic chips [6], high resolution imaging [7]. Recently, the main emphasis has been on obtaining a broad control of focusing, steering and canalization of light [8], thus giving rise to many advanced applications to which we can include Lidar or wireless telecommunications. Within this framework, metasurfaces are seen as one of the most promising plasmonic architectures. However, there are some drawbacks that must be overcome, i.e.: high losses caused by strong local surface plasmon polaritons between nano elements (unit cell), which often degrade the phase shift. Furthermore, k wavevector entries are limited by elements size. Very recently, Zhengyu et al [9], considered the use of the HMMs for fingerprint purpose, and described the occurrence of the intrinsic hyperbolic modes that takes place when the IFC gets an open bounded hyperboloid shape. In this work, we propose a tunable low-loss multifunctional platform based on plasmonic hyperbolic metamaterial (PHMM), composed of indium tin oxide (ITO) and silica (SiO2). Our scheme enables light to be transferred for far field and eventually focusing it via adapting the use of double and single edge tapered waveguides respectively on top of the HMM. Finally, we functionalize the PHMM for the use as a fingerprint in the near-IR range.

2. Method

In our study, the ITO with a sheet resistivity of 100 Ohm/sq was characterized in the range from 0.3 to 2.5 µm for obtaining all the necessary parameters such as: refractive index (n), extinction coefficient (k) and the real and imaginary part of the permittivity retrieved by Drude model. Full-wave numerical analysis were performed via ANSYS/Lumerical FDTD solver for three different architectures: HMM with double and single edge tapered waveguide on top and HMM stack for fingerprinting.

2.1. Method HMM with tapered waveguides

Numerical simulations were performed for a HMM composed of 21 stacks of 20 nm ITO and 20 nm SiO2 at the open bounded hyperbolic regime (Type II) at a wavelength of 2 µm with a silica-based double (DETW) and single (SETW) edge tapered waveguide respectively, designed with the following equations:

\[(DETW) = 0.4\times2.0 - 0.15\times x + 0.05 \quad (1)\]
\[(SETW) = 0.4\times1.5 - 0.15\times x + 0.05 \quad (2)\]

A perpendicular dipole source, placed in the vicinity of the first unit cells, was used to illuminate the stack.

2.1.2. Method HMM as a fingerprint

For the fingerprinting purpose, a 11 stacks composed by alternating layers of 20nm ITO and SiO2 20nm was functionalized. To illuminate the stack, two perpendicular dipole sources with 80 nm inner distance were used. To ensure algorithm stability in both cases, we used a uniform spatial grid with 100 nm step and additional mesh over the HMM with 10 nm step.
3. Results and Discussion

We report the electric field distribution (on a logarithmic scale) for a 21 stacks HMM made by 20 nm ITO/20nm SiO$_2$. A perpendicular dipole source (placed on bottom of the HMM) oscillating at 2 µm wavelength (type II regime). Here, the light gets a high k-modes with typical cone shape (volume plasmon polaritons), clearly seen in Figure 1(a). Those modes, in a normal circumstances, goes evanescently in the air at the exit layer of the HMM. In our case we coupled those modes with a silica based double edge tapered waveguides. Numerical calculations clearly show that the k-modes are first coupled by the tapered waveguide and then a squeeze and trapping phenomena occur, thus leading light to go through the waveguide first and eventually moves far from it. We observe exactly the same in Figure 1(b). The only difference is that we have a single edge tapered waveguide (made by silica) that focuses the light on a spot indicated by the arrows.

Figure 1: Electric field distribution (on a logarithmic scale) of 21 stack HMM composed of alternating 20 nm ITO and 20nm SiO$_2$ with a double (a) and single (b) edge tapered waveguide on top.

In order to investigate the HMM as a fingerprint we used 11 stacks of 20 nm ITO/20 nm SiO$_2$. The conical propagation narrow beams inside the HMM are depicted in Figure 2 (a-c) respectively for sweeping wavelengths: 2.500 µm, 2.244 µm and 1.837 µm.

Figure 2: (a)(b)(c) Electric field distribution (on a logarithmic scale) of 11 stack of HMM composed of alternating 20 nm ITO and 20nm SiO$_2$ respectively at wavelengths: 2.500 µm, 2.244 µm, 1.837 µm.

It is worth noting that there is high dependency of propagation beams with respect to the wavelength, with a tendency to be narrow at shorter wavelengths. Thus, this ability to support intrinsically conical narrow light beam leads to the use of HMMs to encode spatial information exploiting the fingerprint process.

4. Conclusions

We have investigated an innovative tunable multi-platform hyperbolic metamaterial for guiding and focusing light, employing, to the best of our knowledge, for the first time a unique architectures composed of tapered waveguides placed on top of the HMM for manipulating the light propagation at the nanoscale. This allows the use of such device in far-field waveguides and biosensing applications. Importantly, a novel sub-wavelength fingerprint imaging approach has been shown, thus paving the way for the next generation of imaging/sensing metamaterials.

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References

Dispersion, tunability and active properties of chosen structures of hyperbolic metamaterials

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Abstract
Numerically simulations of hyperbolic metamaterial properties metal-dielectric type structures were described. Propagation of electromagnetic wave from VIS and NIR range through hyperbolic metamaterial structure have been analyzed. The characteristics describing components of permittivity tensor in these materials were presented. Relations between properties of different type of hyperbolic metamaterial have been discussed. Different dielectric/conductive stacks for example: Al/HfO$_2$, graphene/SiO$_2$, Ag/Si, were tested. The tunability of hyperbolic dispersion of graphene-based HMM by varying the chemical potential, was reported as a tunable narrowband blueshift in reflectance, especially for different incidence angle in TE/TM modes. Furthermore, type II and type I hyperbolic dispersion and an effective metal behavior were observed. The results of the simulation of the Purcell factor for a dipol placed on the top of a multilayer hyperbolic metamaterials structure of alternating thin layers of silver and silica with a thickness of 20 nm were presented.

1. Introduction
Hyperbolic metamaterials (HMMs) are special new class of multilayer structures which can have unique properties, like hyperbolic dispersion, tunability and enhancement of density states. HMMs are classified as Type I and type II. In the case of Type I ($\varepsilon_\parallel > 0$ and $\varepsilon_\perp < 0$) the materials behaves as a dielectric in the plane xy and as a metal in the z direction. Type II ($\varepsilon_\parallel < 0$ and $\varepsilon_\perp > 0$) instead has two components of the dielectric tensor negative (in-plane) whereby the HMM behave as a metal. Their unique properties such as for example: negative index materials, near-zero and indefinite permittivity or permability indices, backward wave, create completely new perspectives of manipulation of electromagnetic radiation and determine many attractive potential applications of HMMs: in antenna, waveguide engineering, microscopy, imaging below the diffraction limit, perfect absorbers and others [1-3].

2. Results and discussion
Different unit cell stack structure with 10 nm for the Al layer and 3nm for the HfO$_2$ were simulated. This metastructure presents a hyperbolic type II isofrequency dispersion a several feature have been observed. By changing the number of unit cell, as well changing the fill fraction, is possible to have a narrowband reflectance as switchable material in Near-IR. These features make Al/HfO$_2$ one of the suitable metamaterial in the NIR and MIR range.

Scheme of Al/HfO$_2$ multilayer hyperbolic structure is given at Fig. 1.

![Fig. 1. Scheme of Al/HfO$_2$ multilayer hyperbolic structure.](image)

For stacks with graphene effective permittivity can be written as [7]:

$$\varepsilon_g = 1 + \int \frac{\sigma(\omega, \Gamma, \mu_c, T)}{\omega \varepsilon_0 \varepsilon_g} \, d\omega$$

where $\varepsilon_0$ is the vacuum permittivity and $\sigma$ is the conductivity of a single layer of graphene. The surface conductivity for a single layer of graphene is given by Kubo formula [8]:

$$\sigma(\omega, \Gamma, \mu_c, T) = \sigma_{\text{intra}} + \sigma_{\text{inter}}$$

$$\sigma_{\text{intra}} = \frac{-ie^2}{\pi \hbar (\omega + i \Gamma)} \int_0^\infty \xi \left( \frac{\partial f_d(\xi)}{\partial \xi} - \frac{\partial f_d(-\xi)}{\partial \xi} \right) \, d\xi$$

$$\sigma_{\text{inter}} = \frac{ie^2 (\omega + i \Gamma)}{\pi \hbar^2} \int_0^\infty \frac{(\omega d(-\xi) - f_d(\xi))}{(\omega + i \Gamma)^2 - 4(\xi/h)^2} \, d\xi$$

$$f_d(\xi) = \frac{1}{\exp((\xi - \mu_c)/(k_b T)) + 1}$$

where $\omega$ is the angular frequency of the incident electromagnetic wave, $\Gamma$ is the scattering rate which we set equal 0.1 meV, $\mu_c$ is the chemical potential, $T$ the temperature, $e$ is the electron charge, $\hbar$ is the reduced Plank constant and $k_B$ is the Boltzmann constant. The equation (5) is the Fermi-Dirac distribution. The two conductivity terms in (3) and (4) are referred to as the intraband and interband terms, respectively.
3. Conclusions

Hyperbolic metamaterials based on Al/HfO₂ have been investigated. Since this metamaterial presents a hyperbolic type II isofrequency dispersion a several feature have been observed; by changing the number of unit cell, as well changing the fill fraction, is possible to have a narrowband reflectance as switchable material in Near-IR. These features make Al/HfO2 one of the winning metamaterials in the Near and Mid-IR range as a spatial filter, reflection modulator for optoelectronic applications [4]. A type I, type II hyperbolic dispersion and an elliptic dispersion behavior has been comprehensively investigated and verified by the spatial distribution of reflectance in graphene/SiO₂ metastructures. Importantly, transitions between different types of dispersions were examined by determining the resonance frequencies [5].

Blueshift in hyperbolic metamaterials structure in mid-IR frequencies was observed for multilayer structures Ag/Si to thermal emission engineering. The most important consequence of unbounded dispersion of Type I and Type II of HMMs is a divergent photonic density of states resulting in an enhancement in the spontaneous emission of dipole emitters placed in the vicinity of HMM leading to a metamaterial based broadband Purcell effect and in the result the possibility of control of gain/absorption in tunable hyperbolic metamaterials [5]. Photonic density of states, like its counterpart for electrons, is very important in the design of advanced electronic and photonic devise that use The results of the simulation of the Purcell factor for a dipol placed on the top of a multilayer hyperbolic metamaterials structure constructed of alternating thin layers of silver and silica with a thickness of 20 nm. Received results may suggest that it is much easier to induce amplification of the emission of an emitter located on the surface of the HMM structure type I than type II [6].

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References

Nanostructured optical fibers

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Abstract
The nanostructuring technique allows to fabrication of all-glass optical fibers with properties not differing from the existing solutions. Moreover, nanostructuring makes it possible to break the circular symmetry of the fiber structure and fabricate new fibers, impossible to manufacture with other methods, as well as to optimize the fiber optical parameters more extensively.

1. Introduction
The optical fibers are widely used in various fields of modern technology, ranging from telecommunications, metrology, high energy transmission, nonlinear effects, and medical applications [1]. The variety of applications has forced the development of various fiber structures made of different materials that optimize different parameters of light propagation. The basic optical fiber structures can be divided into three groups: all-glass fibers, photonic crystal fibers, and antiresonance fibers. Photonic crystal fibers allow, for example, for a wide range of modification of dispersion properties and for breaking the symmetry of the fiber structure [2]. Antiresonance fibers offer, among other things, low losses over a wide wavelength range [3]. However, both of these two approaches have limited applications and are difficult to integrate with classical all-glass fibers. All-glass fibers are the most widely used and new capabilities are being found. However, the current progress in the development of all-glass fibers is determined by the performance of the MCVD (Modified Chemical Vapor Deposition) method and other variations of the CVD method of fabricating preforms [4]. First of all, these technologies limit the variety of structures considered to rotational symmetry. It is also problematic to obtain high or very low contrast between refractive indices in different areas of the fiber and also structures with the complex distribution of refractive index gradient.

2. Nanostructured fibers
So, there is a need for new types of optical fibers and new technologies for their fabrication. One of such techniques is the nanostructuring method [5-7]. Nanostructurisation is based on arranging, according to a designed pattern, a preform of at least two glasses differing in refractive index (Fig. 1). When the fiber is drawn, the size of inclusions, of one glass in the other, is several times smaller than the wavelength (Fig. 2). Thus, the refractive index distribution can be treated as continuous, and the refractive index profile can be described using the Effective Medium Theory (EMT) and Maxwell-Garnett mixing formula [8].

Figure 1: Scheme of fabrication of optical fiber using nanostructuring method
In the presentation, we will show, first, that nanostructuring makes it possible to obtain all-glass optical fibers with properties that do not differ from existing all-glass fiber solutions. Secondly, we will show that nanostructuring offers new possibilities. In particular, we will present experimental results on dispersion engineering and supercontinuum generation in nanostructured fibers. The results of work on the fabrication of large mode area fibers, birefringence fibers, and active fibers with Bragg gratings.

Acknowledgements

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References


Figure 2: Nanostructured fiber: a) fiber design, b) core of the drawn fiber, c) preform stacked with the two types of glass, d) magnified section of the preform, e) SEM image of the drawn fiber.
Block copolymer directed nanoarchitectures for the design of novel optical materials.

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Abstract
Several types of block copolymers have been used as templates to produce well-defined dielectric and metallic nanostructures in 3D or 2D, with high degree of order and tunability. Resulting structures have shown interesting optical properties such as high-index metasurfaces or antireflective coatings.

1. Introduction
Metallic and dielectric nanoarchitectures are attracting increased attention for optical applications, due to their unique electromagnetic properties. These nanocomposites are prominent in optical metamaterials, which are artificially structured materials engineered to gain optical properties not only from their composition, but from their design. Their geometry, size and arrangement can affect the propagation of light in an unconventional manner, giving rise to properties which are not available in bulk materials. Metamaterials and nanophotonic devices are classically fabricated by lithography techniques, but alternative simpler techniques are needed to reach characteristic sizes on the tens of nanometers length scale.

2. BCP co-assembly based dielectric mesoporous structures.
Co-assembly approach relies in the combination of inorganic precursors with organic structure-directing agents in solution such as surfactants or block copolymers (BCPs). Following this approach, and in combination with the so-called persistent micelle templating method, inorganic precursors (typically aluminosilicate and TiO2 sol-gel derived) are embedded into the corona of amphiphilic poly(isobutylene)-block-poly(ethyleneoxide) (PIB-b-PEO) micelles via preferential supramolecular interactions. After deposition on a silicon substrate, the hybrid composites are transformed into an ordered inverse opal-type mesoporous structure by thermal calcination (Figure 1).

Figure 1. Schematic of the BCP persistent micelle templating method followed during this work.

The use of BCP as structure-directing agent offers reliable control over porosity and pore size. While porosity is commonly tuned by the mixing ratio between organic and inorganic precursor, the pore size is predominantly determined by the molecular weight of the sacrificial block forming the micelle core. However, bespoke BCP synthesis remains a considerable effort, thus impeding continuous pore tuning for nanostructure optimisation. Furthermore, the intrinsic polymer dispersity presents challenges to the pore size homogeneity. Other difficulties arise from the fact that most widely established techniques for porosimetric evaluation in bulk materials, such as nitrogen physisorption or mercury intrusion, are difficult in thin film configurations, mostly due to the small total surface area and pore volume of the active film.

In this work, we present the application of BCP chromatographic fractionation to create tailored inorganic mesoporous thin films.[1] Crucially, we identify the role of molecular weight, composition and dispersity on the
resulting pore size distribution. We first isolate different BCP fractions from a polydisperse amphiphilic PIB-b-PEO sample and characterize their molecular weight and composition via gel permeation chromatography (GPC) and nuclear magnetic resonance (NMR). Different BCP fractions then serve for formulation with aluminosilicate sol for the fabrication of tunable inorganic mesoporous structures (Figure 2). Moreover, reliable structural characterization of mesoporous thin films with respect to their pore morphology, pore size distribution, surface area and overall porosity are provided by the combination of different characterization techniques.[3] Thus, atomic force microscopy (AFM), grazing incidence small-angle x-ray scattering (GISAXS) and ellipsometric porosimetry (EP) are compared for first time side-by-side for their porosimetric capabilities.

3. BCP templating based plasmonic metasurfaces

Contrary to co-assembly approaches, where self-assembly and inorganic incorporation occurs simultaneously, templating techniques rely on the use of self-assembled BCP films as templates for selective incorporation of inorganic materials. Different strategies e.g. metallic evaporation, atomic layer deposition or sequential infiltration synthesis have been developed in order to obtain inorganic replicas from the original BCP films. However, in terms of optical architectures fabrication, is aqueous metal reduction approach the one that has been revealed as the most versatile, straightforward and inexpensive fabrication method.

![Figure 3A](image1)

![Figure 3B](image2)

![Figure 3C](image3)

Figure 3. A) AFM topographical images of the three sizes gold NP hexagonal arrays obtained using three different molecular weight BCP as template. B) SEM images of discreet gold nanoparticle arrays formed on a silicon substrate using a PS-b-P2VP BCP template. C) AFM topographical images of the different steps of the process to obtain bimetallic raspberry-like nanoclusters by BCP multi-layer self-assembly.

In this work, we present the high versatility that BCP templating offers for optical metasurface fabrication. In a first step, different molecular weight poly(styrene)-block-poly(4-vinyl pyridine) (PS-b-P4VP) BCP self-assembled films were used as templates for the fabrication gold arrays, regularly organized in a hexagonal lattice.[3] BCP macromolecular engineering allowed complete tuning of the structural parameters of the created arrays, i.e., the nanoparticles (NPs) diameter, the interparticle distance and the NP height (Figure 3A).

In a second example, perpendicular lamellar structures of poly(styrene)-b-poly(2-vinyl pyridine) (PS-P2VP) BCP were used as scaffold to create gold decorated surfaces.[3] In this case, the shape of the produced gold NPs was tuned by varying the metal content within the P2V lamellae, using different impregnation conditions. This resulted in different nanofeature shapes from well-defined Au dots to rodlike particles of increasing aspect ratio (Figure 3B).

Finally, more complex structures were prepared using more elaborated fabrication approaches. In this sense, on-demand bimetallic Au@Al2O3 raspberry-like nanoclusters has been fabricated using BCP multi-layer self-assembly strategy (Figure 3C).[3] More generally, different hybrid structures, combining not only different materials but also different morphologies such as cylinders and lamellae have been created following this method. The precise control on the shape, structure, size and materials obtained with the previously described fabrication processes, allows a complete modulation of the optical response of the fabricated metasurfaces. Indeed, highly tuneable refractive index and low impedance metasurfaces have been created following these approaches. GISAXS, AFM, Scanning Electron Microscopy (SEM) and X-ray Photoelectron Spectrometry (XPS), have been used to follow each step of the fabrication process. Besides, optical properties were studied by variable-angle spectroscopic ellipsometric.

4. Conclusions

Block copolymer templating and co-assembly has been show a great potential to produce well-defined plasmonic and dielectric nanostructures in 3D or 2D, with specific and tuneable optical properties.

Acknowledgements

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References

Abstract
Polymeric carbon nitride (pCN) has emerged as an attractive material for nano-optical devices, offering a confluence of desirable mechanical properties, high intrinsic refractive index, excellent transparency in the visible region and exploitable anisotropy. In this contribution, we present a combined theoretical and experimental investigation of pCN-coated, gold double-fishnet metamaterials. Our full-dimensionality, finite-difference time-domain calculations are complemented with state-of-the-art device fabrication procedures which make possible the realization of such pCN-based metamaterials, and we compare our theoretical predictions directly with experimental measurements.

1. Introduction
Traditionally, the functionality of electromagnetic metamaterials has been impacted most profoundly by the morphology and spatial arrangement of their metallic or dielectric constituents. However, contemporary materials science provides an alternative yet complementary pathway to metamaterials innovation, offering unconventional material platforms towards a new generation of nano-optical devices that are efficient, cost-effective and sustainable. In particular, polymeric carbon nitride (pCN), a semiconducting polymer with remarkable mechanical flexibility, high intrinsic refractive index and transparency in the visible region, has recently been synthesized by thermal chemical vapor deposition in the form of highly homogeneous films over large surface areas and with tunable nanoscale thickness for the first time [1]. The experimental feasibility of producing such high-quality, pCN thin films merits complementary theoretical investigations exploring the potential of this material as a basis for organic nanophotonic devices achieving enhanced light-matter interaction, which to date have been dominated by purely inorganic media such as crystalline TiO$_2$.

In this contribution, we present a tandem theoretical and experimental investigation of pCN-coated, gold double-fishnet (DF) metamaterials designed with both rectangular and circular holes (see Fig. 1). Full-dimensionality, finite-difference time-domain (FDTD) calculations for the absorption-transmission-reflection (ATR) characteristics of the structure are compared with experimental data, obtained through state-of-the-art device fabrication and optical measurements. Additionally, we discuss the plasmonic behavior of the device in terms of the electric and magnetic near-field distributions, and predict the effective constitutive properties via calculation of the scattering parameters.

2. Theoretical and experimental methodology
2.1. The finite-difference time-domain method
To predict the optical characteristics of pCN-coated, gold DF metamaterials, we employ well-established FDTD methodology [3], as implemented in the high-performance, photonic simulation software package Lumerical (Ansys Lumerical Inc.). Our time-domain simulations provide detailed insight into the spatiotemporal dynamics of the electromagnetic near-field distribution of the device, revealing especially the role of surface-plasmon excitation at the pCN-gold interfaces. Furthermore, calculation of the scattering matrix enables retrieval of the effective parameters of the system, allowing the identification of spectral regions with potential epsilon and/or mu near-zero behavior, as well as negative refraction.
Amorphous pCN thin films were deposited by low-pressure chemical vapor deposition (LPCVD) using melamine (C₃H₆N₆) powder, a nitrogen-rich organic compound, as the precursor. The system was optimized to achieve the desired optical dispersion profile and thin-film thickness based on our previously published, in-house set-up [1]. A SiO₂/Si substrate was used for the deposition of the first 60 nm layer of pCN. The DF layers of gold were then added to the stacking using a physical vapor deposition system and electron beam lithography followed by lift-off, with hole dimensions of 120 nm x 80 nm x 40 nm. A new 60 nm layer of pCN was deposited on top of each gold DF structure using the same LPCVD process aforementioned.

The complex refractive index of the LPCVD pCN thin films was investigated by generalized ellipsometry, revealing not only a high refractive index in the visible range, but also a large uniaxial anisotropy between the in-plane (x or y, parallel to the surface) and out-of-plane (z, normal to the surface) directions, which originates in the alignment and orientation of the molecules in vacuum-deposited organic thin films [4].

3. Discussion

Fig. 2 shows sample, theoretical ATR spectra of pCN-coated, gold DF metamaterial structures featuring rectangular and circular holes. The geometrical parameters are as given in the caption of Fig. 1. The spectra each present a direct transmission peak around 510 nm, by virtue of the thinness of the gold films, as well as a noticeable minimum around 620 nm, whose sensitivity to the hole geometry points to a likely origin in surface plasmon excitation at the pCN-gold interface, or excitation of a hybrid surface-plasmon hole-waveguide mode. Beyond the minima however, the spectra differ markedly. Whereas the DF system with rectangular holes supports a broad transmission (T~5%) band extending to the longest wavelengths considered, the circular holes give rise to a prominent peak (T~20%) attributable to extraordinary optical transmission. The observation of such behaviors previously discovered for nanostructured metal films, and DF structures in particular, suggests that the pCN-coated system offers much of the same richness, but importantly, is based on a mechanically robust, spectrally lossless and sustainable design.

4. Conclusions

We have reported a combined theoretical and experimental investigation of DF metamaterials coated with pCN, a polymeric, semiconducting material featuring high mechanical flexibility, large intrinsic refractive index and excellent transparency in the visible region. State-of-the-art numerical simulations and experimental characterization provide a comprehensive insight into the optical properties of the system and its potential for the manipulation of light in novel ways. Our research delivers further impetus to the development of sustainable and efficient nano-optical devices, and offers a new platform for the exploration of active (gain-enhanced) nanoplasmonic metamaterials [2].

Acknowledgements

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References


Mid-submicrometre pixelation of InGaN micro-LED displays with high integration capabilities for AR-glasses

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Abstract

InGaN-based blue light-emitting diodes (LEDs), with their high efficiency and brightness, are entering the display industry. However, a significant gap remains between the expectation of highly efficient light sources and their experimental realization into tiny pixels for ultrahigh-density displays for augmented reality (AR). Here, we report using tailored ion implantation (TIIP) to fabricate highly-efficient, electrically-driven pixelated InGaN micro-LEDs (μLEDs) at the mid-submicron scale (line/space of 0.5/0.5 μm). Moreover, we demonstrate high-density TFT and QD C/F integration technologies.

1. Introduction

Due to their inherent high efficiency, brightness, and stability, inorganic Group III–V microLEDs (μLEDs) are being evaluated in next-generation displays for a wide variety of applications [1-3]. Pixelation refers to forming an array of light emitters (pixels) that can be distinctively controlled without crosstalk between neighbors. Mesa etching, which physically removes p-GaN and multiple quantum wells (MQWs) for electrical contact at the n-GaN surface, has long been used for single LED devices and is commonly regarded as a pixelation technique for next-generation μLEDs. However, non-optimized mesa etching exposes damaged surface in the active region, which could lead to much greater non-radiative surface recombination with decreasing pixel size (< 10 μm including submicron), thus significantly reducing efficiency. Surface passivation techniques or core-shell structures have been used to reduce surface recombination. Moreover, integration into driving pixel thin-film transistors (TFTs) is difficult because of three-dimensional (3D) geometry-related process issues, such as poor step coverage. Therefore, a new pixelation strategy is needed to achieve both high efficiency of submicron-scale devices and easy integration into pixel-driving circuitry.

Herein, we report using tailored ion implantation (TIIP) to fabricate highly-efficient, electrically-driven pixelated InGaN microLEDs (μLEDs) at the mid-submicron scale (line/space of 0.5/0.5 μm), corresponding to 8500ppi (RGB). Precisely, this technique exploits ion implantation (IIP) of a small-thickness pixelation mask at ~100°C using heavy ionic species with a tilt angle of 0° and with low energy and dose, with their pixelation mechanism revealed. Furthermore, we describe the monolithic integration of TIIP pixelation with low-temperature polysilicon (LTPS) pixel circuits to demonstrate 2000-ppi (pentile) display prototypes and 5000-ppi compatible core technologies including quantum dot color converters (QD C/Cs) [4].

2. Main

We describe high-ppi pixelation by TIIP and integration of pixel TFTs and QD C/Cs.

2.1. Submicrometre pixelation by TIIP

Without elaborate surface passivation, mesa etching should create substantial nonradiative recombination centers that significantly decrease efficiency, particularly at the submicron size because of increased surface-to-volume ratio. In contrast, IIP can achieve the planar-geometry pixelation without needing to expose any surfaces. Despite these advantages, micron-sized pixelation by ion implantation is highly challenging. We investigated the TIIP conditions for a number of implantation conditions and pixel sizes using fluorescence photoluminescence (PL) microscopy TIIP spatially confines the implanted region precisely, with minimal lateral spreading. Thin implantation mask thickness is the critical parameter for optimal TIIP. Using a 0° tilt angle and heavier ions, including Ar+ or Kr+, is also beneficial. Minimal ion energy and dose should be used because high values degrade pixelation contrast. Ion energy is more influential than fluence. We verify the excellence of TIIP pixelation by experiment. A 200-nm-thick Ti mask is formed under the TIIP conditions of Ar+ implantation at 100°C, a tilt angle of 0°, energy of 5 keV, and dose of 2 × 10^{12} cm^{-2}. PL microscope images are displayed for various pixel densities (4800, 6600, and 8500 ppi) in Figure 1. The EL lumiance for TIIP pixelation is 14,290 and 55,835 nit at 4,800 and 300 ppi, respectively, under the current density of 4.9 A/cm². More importantly, the TIIP-pixelated LEDs are intrinsically invulnerable to misalignment-induced electrical leakage due to absence of n-GaN surface opening, which should facilitate the fabrication for ultra-high-density μLEDs.
2.2. Integration of TIIP pixelation into TFT pixel circuits and QD C/C

Owing to the planar geometry, TIIP pixelation is readily incorporated via monolithic or bonding integration into any high-resolution pixel-driving circuits in high-ppi µLED displays. For example, 2-transistor/1-capacitor (2T1C) pixel circuits based on LTPS are fabricated monolithically on the TIIP/charge-blocking layer (CBL) structure. Figure 2a,b presents TIIP/CBL-pixelated LEDs operated by 300/600/2000 ppi LTPS-TFTs. The 2000 ppi (pentile) LTPS-TFTs have width/length (W/L) of 2 μm/2 μm. Furthermore, we verify the transfer characteristics of p-Si TFT even at W/L of 1 μm/1 μm, which corresponds to 4,000 ppi (pentile) pixel circuits. Finally, the TIIP/CBL LEDs are readily assembled with a QD color converter (C/C) pattern. For example, we applied QD C/C for 300-ppi RGB displays (Figs. 2c). Furthermore, we are under development of the backside-exposure technique for high-resolution patterning of QD C/C (Fig. 3), which is essential for full-color microdisplays in AR glasses. The backside-exposed QD layer begins crosslinking from the bottom side, which enables fine patterning with controlled PR thickness.

![Figure 1: Photoluminescence (PL) microscopy images by TIIP pixelation for three different high-density pixel sizes (4800, 6600, 8500 ppi).](image)

![Figure 2: Monolithic integration of TIIP-pixelated LEDs with TFTs and quantum dots. a, TFT-driven electroluminescence (EL) pixel images of the unflipped structure (Fig. S3b): 300 ppi (left) and 600 ppi (RGB) (right), b, TFT-driven EL images of the flipped architecture: (top left) fully-on image, (top right) moving image, (bottom left) 300 ppi (RGB) pixel image, and (bottom right) 2,000 ppi (pentile) pixel image. c, Quantum dot (QD) integration of barrier rib onto 300 ppi (RGB) LEDs (top left), QD color converter (top-center and right) and corresponding full-color images including separate R, G, B, and moving images (bottom).](image)

Figure 3: Schematics of back-side exposure techniques for high-resolution patterning for QD C/C patterning. a, Scatterer-PR coating and backside exposure. b, development of Scatterer-PR and coating of green-QD PR. c, development of green-QD PR and coating of red-QD PR. d, development of red-QD PR.

3. Conclusions

We demonstrate TIIP as mid-submicron sized, electrically-driven pixelation of InGaN-based LEDs with its pixelation mechanism revealed. PL microscopy of submicron-sized pixels clearly reveals that luminance, intra pixel uniformity, and pixel distinctiveness in TIIP pixelation are well maintained. TIIP pixelation can achieve stable, leakage-free EL luminance even at mid-submicron sizes (W/L = 0.5 μm/0.5 μm, 8,500 ppi (RGB)). Furthermore, owing to planar geometry, the TIIP-pixelated LEDs have excellent integration capability with small-sized TFT pixel circuits and QD C/Cs. We strongly believe that TIIP pixelation is the ideal solution for full-color ultrahigh definition microdisplays for AR glasses.

References

Gold nanoparticles: from plasmonic field enhancement and luminescence to nanofabrication

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Abstract

The two-photon-excited luminescence of gold nanoparticles is studied in detail. A phenomenological model is proposed which reveals the importance of field enhancement at the plasmonic NP resonances for both plasmon enhanced absorption and plasmon enhanced emission, with surface effects also playing an important role. Beyond these fundamental aspects, we show that plasmonic hot spots can also interestingly be taken into profit for the realization of advanced hybrid nanostructures for photonics.

1. Introduction

Although bulk gold is known to present very low luminescence quantum yield, gold nanoparticles (NPs) can present a huge nonlinear luminescence with an apparent high influence of the particle shape. The origin of plasmonic luminescence remains a subject of intense discussions [1]: after summarizing the results obtained in our lab regarding the two-photon luminescence (TPL) of colloidal gold nanorods or nanobipyramids, I will present and discuss a phenomenological model considering both the local field enhancement effects at the NP and the different size-dependent plasmon relaxation processes. I will then show that the full control of the plasmonic near field enables the controlled realization of hybrids nanostructures coupling NPs with molecules or quantum dots (QDs) down to the ultimate level of single emitters.

2. Plasmonic luminescence

The TPL of Au nanorods was investigated at the single-object level, combining polarization-resolved TPL and simultaneously acquired topography using atomic force microscopy (AFM). An in-depth study of the influence of both the wavelength and polarization of the excitation beam was carried out. We demonstrate that the nanorods TPL results from two subsequent steps involving both the longitudinal and the transverse surface plasmon resonances of the nanorods: an increase of electron-hole generation first results from local electric field enhancement at the longitudinal plasmon resonance; these electron-hole pairs then recombine radiatively benefiting from the nanoantenna effect at the nanorods transverse plasmon band [2]. A phenomenological model is proposed considering both the local field enhancement effects at the nanorods and the different size-dependent plasmon relaxation processes. BEM (Boundary Elements Method) simulations are used to compute the fields at both the transverse and longitudinal plasmon resonances. A good fitting of the experimental data is obtained confirming the proposed origin of the plasmonic luminescence, evidencing moreover the importance of surface effects. In a next step, the influence of incident power was investigated using the conditions (polarization and wavelength) within which the maximum TPL could be obtained. Given its origin, we show that TPL is a highly sensitive tool for tracking tiny changes resulting from the photo-induced reshaping of nanorods [3], the high anisotropic character of TPL making it also an interesting way to characterize the organization of nanorods [4].

3. Plasmon controlled nanofabrication

In addition to enhancing the luminescence, plasmonic hot spots can also be advantageously used to activate chemical transformations directly and locally on specific areas at the surface of NPs. Plasmon-mediated photochemistry has now become an active area of research in nanoscience since it opens many applicative prospects from energy conversion and photocatalysis, to phototherapy and nanofabrication. More particularly, plasmon based nanoscale functionalization interestingly enables e.g. the realization of hybrid nanostructures with specific functionalities. As an example, using surface plasmon-triggered two-photon polymerization of a photosensitive formulation containing decreasing concentrations of QDs nano-emitters, we have recently demonstrated the possibility to trap single QDs in the vicinity of gold nanocubes, with preliminary observation of a polarization-
driven nano-switch in the single photon emission regime [5]. Although it opens up new perspectives and has already been the subject of numerous demonstrations, the exact mechanisms of plasmon triggered nanoscale polymerization remain however unclear and controversial. After evidencing that plasmon controlled Free Radical Polymerization of Acrylates is obviously a purely photochemical process under mild illumination conditions [6,7], I will present and discuss into more detail that other routes are also possible. Indeed, plasmon induced chemistry is directly dependent on plasmon decay which occurs through competitive relaxation processes that are dependent on the nature of the metal (Au, Ag, ...), the irradiation conditions, the morphology of the NP and its surroundings. Beyond purely photochemical effects (PE) through local near field electromagnetic enhancement, two other processes might come into play : electronic effects (EE) through the transfer of hot charge carriers from the excited NP to nearby chemical species; or Thermal effects (TE), through the heating resulting from the lattice thermalization following electron-phonon interactions. The unravelling of these phenomena, as well as the quantification of their potential synergies, appears now as a key point towards new progress and applications in the field of plasmon driven nanofabrication.

References


Local enhancement and control of light-matter interaction
Near-field spectroscopy of Silicon Carbide phonon polaritons resonators

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Abstract

Antennas supporting surface phonon polaritons are an interesting alternative to common plasmonic resonators in the infrared region, due to their reduced losses and higher field confinement. However, many applications involving SPhPs antennas require the knowledge of their near-field response, which cannot be directly inferred from common far-field measurements. We study the near-field spectral response of arrays of Silicon Carbide antennas by means of scattering near field microscopy and discuss the influence of the AFM tip on the experimental results.

1. Introduction

The loss in metallic antennas at optical frequencies has limited their employment in a variety of applications where high quality factors and low losses are required [1]. A class of materials showing properties similar to plasmonic materials are polar dielectrics. Polar dielectrics are characterized by the presence of infrared (IR) phonons with strong dipolar moments that can lead to the existence of region where the real permittivity becomes negative, named Reststrahlen band. Surface phonon polaritons (SPhPs) are mixed light-waves excitation analogous to plasmons, existing in the Reststrahlen band [2]. Thanks to the weaker phonon-phonon scattering, SPhPs are characterized by much longer lifetimes if compared to plasmons (on the order of picoseconds, two orders of magnitude higher than for plasmons). Consequently, SPhPs antennas provide much stronger field confinement and lower losses if compared to analogous plasmonic structures in the IR. However, many envisioned applications require knowledge of the near-field spectral behavior of the system under investigation, which cannot be obtained or easily inferred from far-field measurements. Nevertheless, it has been shown that scattering near field optical microscopy (sSNOM) can indeed correctly grasp the near-field response of an optical system [3].

2. Results and Discussion

The main limitation of SPhPs is the narrow frequency band in which they can be excited. As such, 3C Silicon carbide (SiC) is particularly interesting thanks to its wide Reststrahlen band, extending from $\omega_{r0} = 796$ cm$^{-1}$ to $\omega_{r10} = 973$ cm$^{-1}$. On top of that, the low optical losses of SiC make it one of the best materials for fabricating antennas supporting localized SPhPs [2]. Among different geometries, arrays of SiC pillars have attracted considerable attention thanks to their rich electromagnetic response, including broadly tunable modes [4] and nonlinear response [5]. The SiC pillar structures are fabricated by dry etching a 3C-SiC layer through a hard mask fabricated by standard e-beam lithography, so that the pillars are supported by a SiC substrate. In Fig. 1(a) an SEM image of a portion of one of the arrays is reported, along the experimental (b) and simulated (c) reflectance spectra for different arrays with varying spacing $P$.

Figure 1: (a) SEM of a portion of a SiC pillars array. Experimental (b) and simulated (c) reflectance spectra for different array spacing $P$. The different modes are highlighted by dots.
The far-field optical response of the system is well understood as its modes result from the coupling of simple longitudinal and transverse resonances of a single pillar to the bare SiC surface supporting SPhPs at $\omega \approx 950 \text{ cm}^{-1}$ [6]. Three main modes can be identified from the spectra, a monopolar mode (M) redshifting with increasing $P$ and two transverse dipolar resonances (TD1 and TD2) at $\omega_{TD1} = 921 \text{ cm}^{-1}$ and $\omega_{TD2} = 955 \text{ cm}^{-1}$ for all the arrays. The simulated field profiles for the three modes for the array with $P = 2.5 \mu\text{m}$ are reported in Fig. 2.

![Figure 2: Simulated field profiles for the monopolar mode (a), the first transverse dipolar mode (b) and the second transverse dipolar mode (c).](image)

We investigate the near-field response of the arrays by distinguishing measurements taken with the tip on one of the pillars, or on the substrate between them, as shown in Fig. 3.

![Figure 3: Near-field measurements of the different arrays when placing the AFM tip on top of a pillar (a) or on the substrate between pillars (b).](image)

The response on the pillars is independent of the array spacing, since we can identify two peaks, marked with green and red dots, at $\omega_{TD1} = 920 \text{ cm}^{-1}$ and $\omega_{TD2} = 945 \text{ cm}^{-1}$ for all the investigated array spacing and matching the frequencies of the far-field measurements. When measuring off pillars the monopolar mode can be identified with the lower energy peak, closely matching the frequency reported in the far-field data. On top of that, another peak appears in the spectra (yellow dot in Fig. 3(b)), redshifting with the monopolar mode, but without a far-field counterpart. To understand the nature of this mode we carry on simulations where we take into account the presence of the AFM tip in the form of a metallic sphere located on top of the pillar. To isolate the contribution of the tip we first solve for the pillar in the absence of the sphere with plane wave excitation, and then we use this field as a background that we subtract from the full simulation including the sphere. In this way we can relate the mode appearing in the near-field spectra as a dark version of the monopolar mode, which is activated by the near-field illumination provided by the dipole induced in the AFM tip. The dark monopole is polarized out of plane like the monopolar mode, but switches polarization along the pillar axis, resulting in zero net dipole moment and no contribution in far-field measurements.

3. Conclusions

In conclusion, we report on the near-field study of the spectral response of arrays of SPhPs SiC pillar resonators in the mid-IR by means of sSNOM. The understanding of the near-field spectral response of SPhPs resonators is of critical importance for their employment in any application requiring near-field interaction. We further employ 3D e.m. simulations to understand the effect of the sSNOM tip in modifying the spectral response of the SPhPs antennas.

References

Tunable Fano Resonance in a Liquid Crystal Colloidal Metamaterial

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Abstract

A colloidal metamaterial is realized by dispersing submicron-sized high-refractive-index dielectric resonators in a nematic liquid crystal medium. Darkfield hyperspectral imaging reveals that when the NLC molecules reorient on application of an ac electric field a doughnut-shaped scattering pattern is obtained, indicating the occurrence of Fano resonance. The theoretical simulation based on the ‘Multi-pole Fano interference model’ confirms the experimental findings. With increasing voltage, the value of Fano parameter q decreases and approaches unity corresponding to an ideal Fano shape.

1. Introduction

Fano resonance is a phenomenon that occurs due to the interference of a broad continuum spectral profile with a narrow line shape.[1] In Fano interference, the phase of the discrete state undergoes sharp changes with a consequent sign reversal; when this interferes with a continuum state of equal strength, simultaneous constructive and destructive interferences occur, which are spectrally placed on either side of the resonance of the discrete state.[2] Such behavior gives a characteristic dip in the scattering spectrum along with an asymmetric spectral profile.[1,3]

In the present work, we have realized a colloidal metamaterial by dispersing high-refractive-index selenium (Se) sub-micron sized spheres[4] in a nematic liquid crystal (NLC) medium. The metamaterial (Se-NLC) exhibits dipolar and quadrupolar Mie resonances in the optical regime, which are tunable with the applied electric field. The darkfield scattering spectra shows the signature of Fano resonance due to the coupling between the broad electric dipole (ED) and narrow electric quadrupole (EQ) resonance modes. The tunability of the Fano parameter, q, is brought about due to the change in the birefringence of the NLC medium on the application of electric field (NLC being soft stimuli-responsive in nature[3]). Further, the far field scattering images show interesting features such as split and doughnut-shaped patterns owing to the optical anisotropy, and the electric field induced Fano resonance in the system.

2. Results and Discussion

2.1. Darkfield hyperspectral imaging

To study the scattering properties of Se particles in LC medium, darkfield hyperspectral imaging (HSI) (Figure 1) was carried out. An ac electric field was applied to the Se-NLC sample sandwiched between the ITO coated substrates, and the HSI spectra from the particles were collected as a function of the applied voltage for 0 and 20 V respectively (See shown in Fig. 1b & c).

![Figure 1](image_url)

**Fig 1:** (Left) Schematic of the darkfield imaging setup. (a) Scattering from a single particle showing split spectra at V~Vth. Scattering spectra along with scattering images (insets), at (b) 0 V and (c) 20 V respectively. FEM simulation based far field spectra at (d) 0 V and (e) 20 V.

From the scattering image shown in Fig 1a, it can be observed that, for 1.4 V, which is just above the threshold voltage, Vth (=1 V), i.e., when molecules start reorienting from the initial planar alignment (‘Fredericksz transition’), the scattering image splits into two. As the voltage is increased beyond Vth, i.e., when NLC molecules completely align along the applied electric field direction, the split images combine into a single scattering image with a dip in intensity in the middle of the bright image forming a ‘doughnut-shaped’ pattern. This scattering image is clearly visible at 20 V (Fig 1c).
2.2. Fano resonance in far field scattering

The scattering spectra along with the Fano fitting profile in the voltage regime 5 to 20 V is shown in Fig 2a. The Fano fitting is done based on the multi-pole Fano interference model,[6,7] 

\[
Q_{\text{scat}} = \left| \sum_{j=1}^{N} \frac{a_j I_j \exp(i\phi_j)}{(\lambda_E - E_j) + i\gamma_j + B} \right|^2
\]

where, \(\lambda_E\) is the incident wavelength in energy (eV), \(N\) is the total number of resonant modes contributing to the scattering, \(a_j, I_j, \phi_j\) and \(E_j\) denote the amplitude, full width at half maximum, phase, and peak energy (wavelength) of the individual resonant modes; \(\gamma\) is the amplitude of the background scattering. The phase values of the two resonant modes, ED and EQ, are extracted, and their voltage dependence is shown in Fig 2b with the phase difference (\(\phi\)) being \(\sim 0.2\) rad at 5 V which increases to \(\sim 0.35\) rad at 20 V. From the \(\phi\) value, the Fano parameter \(q\) is calculated as \(x = \cot(\phi)\), and its voltage dependence is shown in Fig 2c. The \(q\) parameter is the hallmark of the extent of coupling between the two interfering resonant modes with \(q = 1\) being the ideal value for destructive interference between the interference modes. In the present system, the value of \(q\) is 4.4 at 5 V, and on the application of electric field, it decreases, and at 20 V reaches a value of 2.6 (~ 60% decrease). Thus, with increasing voltage, the system shifts towards a perfect Fano interference regime.

The far-field scattering simulated using finite element method (FEM) (Fig 1 d&c) show interesting features which can be understood as follows: When the incident light is traveling along ‘z’ direction with the electric field (of light) polarized along ‘x’ axis (in the case for 0 V), the ED oscillates in ‘x’ direction, giving rise to a toroidal far field scattering pattern with the axis of revolution along ‘x’. Similarly, the MD will have a far field scattering pattern with the axis of revolution along ‘y’ axis (not shown in the Figure). The far field scattering pattern of EQ and MQ exhibits elongated lobes in both forward (z) and backward (-z) directions. Further, the combination of ED along with the strong EQ and MQ gives rise to a forward scattering with an elongated lobe in the propagation direction (See Fig 1d). As the voltage is increased beyond the ‘split-regime’, the NLC molecules orient along the applied electric field with the optic axis perfectly normal to the substrate plane. It is to be noted that the applied electric field and hence the NLC molecular dipoles, both oscillate at a much lower frequency (i.e., 10 kHz) compared to the optical frequencies. Such a condition orients the ED along ‘z’ direction (Fig 1e) which enhances the Fano coupling between ED and EQ; giving rise to a forward scattering lobe with a dip in intensity along the ‘z’ axis in the far field (Fig 1e) leading to a doughnut-shaped scattering image at 20 V (Fig 1e). The top view (xy plane) of the scattering patterns for 0 and 20 V cases substantiates the voltage dependent darkfield experimental observations.

The voltage-dependent changes in the scattering pattern, i.e., from single, through split- to doughnut-shaped images are highly reversible and reproducible over several cycles of the applied electric field indicating the robustness of the SeNLC system. Thus the electric field-driven tunable Fano resonance makes the system a potential candidate for applications such as refractive index sensing and waveguides[11].

References
Nanooptics in Hyperbolic Van der Waals Materials

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Abstract

Polaritons – hybrid light-matter excitations – play a crucial role in fundamental and applied sciences, as they enable nanoscale control of light. In this work, we present propagation of hyperbolic polariton along the surface of the Van der Waals (vdW) material α-MoO₃ with amplitude record lifetimes of 8 picoseconds. Additionally, we will discuss possible applications for the in-plane manipulation of light based on the in-plane and ray-like directional propagation of polaritons. Our findings open new avenues for fully planar photonic technologies at the nanoscale.

1. Introduction

Anisotropic optical materials exhibit numerous distinctive and non-intuitive optical phenomena such as negative refraction, hyper-lensing, wave-guiding and enhanced quantum radiation, which have been demonstrated typically with artificial hyperbolic metamaterials. However, further progress is limited by optical losses and the complexity of metamaterial fabrication.

The recent emergence of low-loss vdW materials opens the door to achieving anisotropic optical phenomena naturally, because their layered crystal structure leads to an intrinsic and strong out-of-plane (perpendicular to the layers) optical anisotropy. Prominent examples are hyperbolic phonon polaritons (PhPs)—infrared light coupled to lattice vibrations in layered polar materials—in hexagonal boron nitride (h-BN), which exhibit long lifetimes, ultra-slow propagation and hyper-lensing effects [1,2]. Interestingly, when the layers of a vdW material are anisotropic (that is, when the permittivities along orthogonal in-plane directions are different), the polaritons are expected to propagate along the layers with an in-plane anisotropic dispersion. When the permittivities are different but of the same sign, the polaritons possess an elliptic in-plane dispersion, in which the iso-frequency contours (slices in two-dimensional (2D) wavevector space (kx, ky) of constant frequency ω) describe ellipsoids. When the signs are different, the polaritons possess an in-plane hyperbolic dispersion, in which the iso-frequency contours are open hyperboloids. Only recently, PhPs with in-plane hyperbolic dispersion have been demonstrated by fabricating an artificial metamaterial out of h-BN flakes [3].

Theory predicts polaritons with both in-plane anisotropies even for natural materials that exhibit an in-plane anisotropy of their electronic or structural properties. However, their experimental observation and verification has so far been elusive. Here we present the first images of in-plane elliptic and hyperbolic polaritons. We found them in thin slabs of α-phase molybdenum trioxide (α-MoO₃), a natural vdW polar semiconductor [4,5]. Remarkably, the in-plane hyperbolic nature of the polaritons along the surface of α-MoO₃ slabs allows for fundamental studies about their propagation and new possibilities including the manipulation of light and hyperfocusing at the nanoscale [6-8].

2. Discussion

To explore the polaritonic response of α-MoO₃, we performed polariton interferometry using scattering-type near-field optical microscopy (s-SNOM) (Fig. 1a). A vertically oscillating metallized atomic force microscopy (AFM) tip is illuminated with p-polarized infrared light of frequency ω and field E₀ in while scanning an α-MoO₃ flake. The tip acts as a polariton launcher and scatterer, since it concentrates the incident field at its apex allowing polariton excitation but also scatters the polaritons reflected to the far field. The polaritons excited by the tip propagate away and are back-reflected at the flake edges, giving rise to interference fringes with a λ/2 spacing. Figure 1b shows s-SNOM near-field amplitude images of an α-MoO₃ flake with thickness d = 250 nm taken at ω = 990 cm⁻¹ and ω = 900 cm⁻¹. At 990 cm⁻¹ (upper image in Fig. 1b), we observe that the fringe periodicity largely depends on the propagation direction, being λ₁ = 950 nm and λ₂ = 1200 nm for the [100] and [001] crystal directions. Apart from the deep subwavelength-scale polariton confinement λ₁,λ₂<<λ₀=11.1 μm. This anisotropy becomes even more marked at ω = 900 cm⁻¹ (lower image in Fig. 1b), where the fringes are seen only parallel to the [001] direction.

We find two Reststrahlen Bands: the upper one (Fig. 1b upper panel), the so-called elliptical regime, in which we have phonon polariton propagation along both directions but with different polariton wavelength in each one; and the lower one (Fig. 1b lower panel), the so-called hyperbolic regime, in which we only have propagation along the
We measured record-high polariton lifetimes of $\tau=8$ ps, which are more than one order of magnitude larger than that of graphene plasmons and four times larger than that of isotopically enriched h-BN. We obtain the lifetime according to $\tau=L/v_g$, where $L$ is the decay length and $v_g$ the group velocity. Decay lengths are calculated fitting s-SNOM profiles to an exponentially decaying sine-wave function and group velocities are worked out by applying a numerical derivative to the $\omega-k$ phonon polariton dispersion (being $\omega$ the incident wavelength and $k$ the phonon polariton wavenumber).

![Figure 1](image.png)

**Figure 1:** (a) Schematic of the s-SNOM experimental configuration used to image an $\alpha$-MoO$_3$ flake. A metallized AFM tip (yellow) is illuminated by p-polarized infrared light of frequency $\omega$ and electric field $E_{\text{inc}}$. It launches polaritons, which are back-reflected at the flake edges and subsequently scattered by the tip. The tip-scattered field is detected by a distant detector. (b) Near-field amplitude images $s4$ of an $\alpha$-MoO$_3$ flake with thickness $d=250$ nm at illuminating frequencies $\omega=990$ cm$^{-1}$ (top panel) and $\omega=900$ cm$^{-1}$ (bottom panel). Extracted from Ref. [4].

### 3. Conclusions

In this work, we show for the very first time in-plane anisotropic phonon polariton propagation in $\alpha$-MoO$_3$ (both elliptical and hyperbolic), with record-high phonon polariton lifetimes. This finding may establish a route to directional control of light and light-matter interactions at the nanoscale. Particularly interesting is the possibility of steering the strongly anisotropic propagation of PhPs in twisted $\alpha$-MoO$_3$ structures [8] or by engineering the dielectric environment [6]. Moreover, owing to the ray-like propagation of PhPs with arbitrarily large wavevectors, it is possible to focus light down to deep-subwavelength focal spots with enhanced performances with respect to isotropic PhPs in conventional media [7].

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Flat Optics and High Quality Factor Nanoresonators with Phonon Polaritons in Van Der Waals Materials

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Abstract

New types of nanophotonic devices based on phonon polaritons in hexagonal boron nitride and molybdenum trioxide are demonstrated. Different substrates (metal, phase change materials or other van der Waals materials) can be used to engineer the propagation of these polaritons. High quality factor resonators using isotopically pure boron nitride are also discussed. Polaritons in van der Waals materials are an excellent mid infrared counterpart to plasmon polaritons in mobile metals.

1. Introduction

Phonon polaritons in hexagonal boron nitride (h-BN) have recently attracted a great deal of attention due to their rich physics, high lifetime and propagation lengths and because they occur in spectral regions where few or no other alternative are available (such as the mid infrared range) [1-10]. This contribution will present several techniques to manipulate the propagation of polaritons using substrate effects (referred to as substrate engineering) [7, 12, 13]. Secondly, by patterning h-BN and molybdenum trioxide (MoO₃) into nanostructures we can achieve strongly confined resonances (into volumes down to five orders of magnitude smaller than the cube of the wavelength) with quality factors in excess of 300, and Purcell factors in the order to $10^6$ [6, 11]. These remainder of this paper provides additional details for these techniques.

2. Substrate engineering

A metallic substrate placed below h-BN (Figure 1a) forms a system where polaritons have a significantly slower phase and group velocity. We characterized this structure with scattering type SNOM (s-SNOM) and photoinduced force microscopy (PiFM) [7]. Another example of substrate-induced effects on polaritons is shown in Figure 2b, where h-BN polaritons propagate with in-plane anisotropy due to the black phosphorous substrate [12]. Finally, re writable flat optics can be achieved by placing h-BN on top of a phase change material (GST) [13]. Using a focused diode laser, it is possible to convert locally the phase of GST from amorphous to crystalline and back, creating nanophotonic structures such as waveguides and metalenses (Figures 1c, 1d).

Figure 1: Substrate engineering of polaritons. a) Hyperspectral imaging with photo-induced force microscopy of polaritons in h-BN on gold, showing increased confinement [7]. b) In-plane anisotropic phonon polaritons in a heterostructure formed by h-BN and black phosphorous [12]. c) Waveguides created by placing an h-BN flake on a GST coated substrate and writing crystalline GST lines in amorphous GST, showing lateral confinement [13]. d) A polaritonic metalens that can focus polariton in a diffraction limited spot in h-BN. Each element is written in the GST substrate below h-BN [13].
Figure 2: High quality factor polaritons. a-b) Phonon polariton resonators in isotopically pure h-BN and their near field spectral response (characterized with s-SNOM). c-d) Phonon polaritons resonators in MoO$_3$ and their near field and far field spectrum. e-f) Exciting resonances in h-BN carrying orbital angular momentum and imaging with phase resolved s-SNOM. A singularity is clearly visible. g-h) Array of h-BN dimer antennas showing electric field enhancement in their gap.

3. High quality polaritonic resonators

Using high quality polaritons in isotopically pure h-BN, we achieved resonators with quality factor in excess of 300 (Figure 2a, 2b). Similar performances can be achieved in MoO$_3$ (Figure 2c, 2d). Disc-shaped resonator can support resonances carrying orbital angular momentum (Figure 2e, 2f) which can be excited with circularly polarized light and imaged with phase resolved s-SNOM. Finally, polaritonic antennas with electric field enhancement in the order of 100 have been characterized (Figure 2g, 2h).

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References

Abstract

Since the introduction of the concept of optical vortex in 1989 a number of methods to generate such beams have emerged. After presenting a timeline tracing the appearance of vortex generation tools in the last 30 years, we will introduce \( p \)-plates—metasurfaces enabling the creation of vortices with high purity. The purity of an optical vortex beam depends on the spread of its energy among different azimuthal and radial modes, also known as \( \ell \)- and \( p \)-modes. The smaller the spread, the higher the vortex purity and more efficient its creation and detection. Photonic devices such as \( q \)- and \( J \)-plates allow to generate vortex beams with a well-defined topological charge or total angular momentum but do not have control over radial modes, resulting in vortices of low purity. Here we present a dielectric meta-surface design based on arbitrary polarization conversion allowing to control at the same time both the \( \ell \)- and \( p \)-mode of a vortex beam. The high purity, sizeable creation efficiency, and impassable compactness make this approach a powerful complex amplitude modulation tool for pure vortex generation, even in the case of large topological charges.
Nanoscale imaging of moiré superlattices in twisted van der Waals heterostructures

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Abstract

Direct visualization of nanometer-scale properties of moiré superlattices in van der Waals heterostructure devices is a critically needed diagnostic tool for study of the electronic and optical phenomena induced by the periodic variation of atomic structure in these complex systems. Conventional imaging methods are destructive and insensitive to the buried device geometries, preventing practical inspection. Here we report a versatile scanning probe microscopy employing infrared light for imaging moiré superlattices of twisted bilayers graphene encapsulated by hexagonal boron nitride. We map the pattern using the scattering dynamics of phonon polaritons launched in hexagonal boron nitride capping layers via its interaction with the buried moiré superlattices. We explore the origin of the double-line features imaged and show the mechanism of the underlying effective phase change of the phonon polariton reflectance at domain walls. The nano-imaging tool developed provides a non-destructive analytical approach to elucidate the complex physics of moiré engineered heterostructures.
Advanced modeling techniques for the design of metasurface devices
Metasurface optimization based on coupled mode theory

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Summary

We develop a coupled mode theory to model metasurfaces. It is much faster than full-wave solvers. Combined with the adjoint method, we show that the CMT approach can be used to efficiently design complex metasurfaces for a variety of functions. As an example, we also demonstrate thermal holograms based on metasurfaces.
Fundamental limitations of ultra-flat Huygens metasurfaces

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ABSTRACT

There are two physical effects that are exploited nowadays to implement flat metalenses requiring $2\pi$-phase excursion, either subwavelength guidance implementing varying propagation delays, or resonant confinement combining two resonances. We compare both approaches and identify possible limitations with the second approach.

Keywords: Huygens’ metasurface, blazed-binary diffractive elements, metalenses

1. INTRODUCTION

The art of metasurface design consists in imprinting rapidly varying phases through high-index-contrast nanostructures etched in transparent films, e.g. titanium dioxide [1,2,3] or semiconductor [4,5,6] layers with a high-index often deposited on a substrate with a lower refractive index. A current open question raising strong interest for possible broad applications is which nanostructures may be used to control independently of each other the phase of the wavefront at sampling separation distances that are subwavelength. The answer to this question is not trivial, and has led, twenty years ago, to the concept of optical phased-array antennas [2], or in recent years to Huygens’ metasurfaces [7].

Overall, two physical effects have been identified to date to achieve the required $2\pi$-phase excursion, either subwavelength guidance implementing varying propagation delays, or resonant confinement combining two resonances, each covering a standard phase range of $\pi$ [8,9]. The purpose of this work is to well understand FUNDAMENTAL differences and similarities, together with the respective advantages and limitations.

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REFERENCES

An efficient global optimization technique based on statistical learning for highly efficient metasurface designs at visible regime

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Abstract

The object of this contribution is twofold. First, we present a brief review of the common inverse design techniques in the field of metasurfaces. Second, we present a global optimization technique based on statistical learning for optimizing highly efficient metasurface devices. Using our method, a light deflection metasurface with efficiency reaching 85% for both TM and TE polarizations has been realized at the visible regime.

1. Introduction

During the last decade, the field of metasurfaces has drawn a lot of attention due to the unprecedented control over the optical properties of light in a very short propagation distance with high resolution [1, 2, 3]. These devices consist of nanostructures defined within a single layer of metal or dielectric materials.

Recently, several optimization methodologies including both local (gradient-based) and global search methods have been considered to tune the parameters of these nanostructures according to the desired applications. Most gradient-based methods require the evaluation of the gradient of the objective function and/or the constraints and are computed numerically at each optimization iteration. Among them, the topology optimization method has been proved to be very efficient [9]. In this method, the optimization domain that corresponds to the physical space containing the nanostructures is decomposed into equally spaced pixels, each characterized with a given local permittivity value. The optimization process is iteratively employed until convergence, at which point a final structure is produced that reasonably satisfies the objective. However topology optimization can be stuck in a local minima rather than the global point in the design space.

Gradient-free approaches are capable of capturing global optima in the design space. In addition, the final optimized results are not influenced by the initialized design. Moreover, most of these methods can deal with a discrete parameter space and non-differentiable objective functions, which are conditions that are generally not handled by gradient-based algorithms. However, the convergence of global optimization algorithms is considerably slower compared to the gradient-based algorithms. Most of the gradient-free algorithms used for metasurface designs are stochastic and based on evolutionary strategies [4, 5, 7].

In this work, we present an efficient global optimization method that belongs to the class of Bayesian optimization and is known as Efficient Global Optimization (EGO) [6, 7]. Contrary to the classical common global optimization strategies like Genetic Algorithm (GA) [4] EGO is not based on adaptive sampling, but on a surrogate model built on the basis of available objective function evaluations. This surrogate mode uses a statistical learning criterion related to the optimization goal (usually called merit function) in order to identify which design (set of parameters) should be tested in the next iteration that would provide better results close to our target.

Here, we use our rigorous Discontinuous Galerkin Time Domain (DGTD) solver from the DIOGENeS software suite dedicated to computational nanophotonics [8] together with EGO, in order to achieve a maximum diffraction efficiency ($\eta(n, m)$, where $n, m$ are the mode indices) at $\lambda = 600$ nm.

We consider a normal incident planewave with electric field polarized in the y-direction, and we aim to maximize the diffraction efficiency of the first order mode $\eta(0, -1)$ (deflect light in the same plane of incidence y-z plane). Thus, we consider a sub-wavelength period in the x-direction (300 nm), and we consider a period of 1500 nm in the y-direction, as it can be seen in Fig. 1(a). We consider cylindrical shaped antennas made of GaN semiconductor, in which the position and diameter together with the height need to be optimized. The 8 optimized parameters are represented by the red circles and white arrows in Fig. 1(a).

In Fig. 1(b), we show the results obtained from the optimization. First, for the EGO model, the shaded region represent the design of experiment (DOE) obtained before the optimization process in the EGO model. Based on these points, a surrogate model is constructed and will be updated during the optimization process to find the global minima below the best point obtained during the DOE phase. The black points represent the data obtained during the optimization phase, where we clearly see that EGO identifies rapidly the best regions (see green curve). More precisely, after only 150 iterations (solver calls), we optimized 8 parameters and obtained a diffraction efficiency around 85% at $\lambda = 600$ nm as indicated in Fig. 1(c), and inferred in
We would like to emphasize that we have studied also the possibility to deflect the light with a broad angle of 75°, which is a crucial issue in the design of highly efficient lenses with high numerical aperture. This requires the period in y direction to be in the order of one wavelength, which means that only two cylinders can be considered in the unit cell and it will be difficult to recover the 2π phase shift. It is important to notice that in the classical way of designing metasurfaces, where manual sweep over the parameters is performed over each single antenna, then the resonators are gathered together according to their single response, in this case, the near field coupling is not taking into account. However, since, we take into account the strong near field coupling between the resonators, we managed to deflect the light by nearly 75 degree with deflection efficiency 74% (data not shown). As a next step, we will consider the multiobjective optimization, in another words, we will optimize the light deflection at different wavelengths simultaneously for small and large angles. Finally, the extension of this work towards the optimization of the large-scale metalenses will be also discussed.

In conclusion, we used our efficient global optimization technique to optimize gradient metasurfaces at visible regime. Our results reveal that we can get up to 85% of diffraction efficiency by optimizing 8 different parameters using only 150 iterations. Our techniques seem to be more efficient than the usual global optimization methods [4, 9] available in the literature in which numerous simulations are required for achieving optimized geometries. This technique opens the door for optimizing more complex metasurface based devices with high performance.

References

Metasurfaces for Divergent Beams and Large-Area Metasurfaces

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Abstract
We will give an overview of our recent work on the design and fabrication of metasurfaces, i.e., dense arrays of subwavelength-sized scatterers (meta-atoms) designed in shape, size, position, and orientation. First, we have developed simulation strategies for large-scale metasurfaces and metasurfaces for strongly divergent beams. Second, we have developed a facile fabrication technique based on an exposed resist to build large-scale metasurfaces. These novel computational and fabrication techniques allow us to achieve metasurfaces with unprecedented functionality.

1. Introduction
The control of light by means of metasurfaces with subwavelength building blocks has been explored in the last few years, giving rise to optical devices with surprising optical response or very light-weight alternatives to bulky optical components [1-2]. Thin flat lenses and other optical components have been obtained by engineering the building blocks of metasurfaces [3-5]. However, most metasurfaces realized so far are essentially designed to modify plane waves and state-of-the-art metasurfaces typically involve several expensive, time-consuming, and potentially hazardous processing steps. While the manipulation of nonplanar wave fronts is encountered in a diverse variety of applications, their control using metasurfaces is still in its infancy. In this talk, we will show that metasurfaces can also be used to manipulate strongly divergent light beams [6]. Subsequently, we will discuss how to build metasurfaces from an exposed standard electron beam resist. This method dramatically cuts the required processing time and cost as well as reduces safety hazards [7].

2. Simulation of large-scale metasurfaces for strongly divergent beams
As an example of metasurfaces for strongly divergent beams, we will show how to design a metamirror able to reflect a Gaussian beam back onto itself [see Fig. 1(a)], focusing at an arbitrary distance from the metasurface with efficiency over 90%. Such a metasurface is a planar equivalent of a concave spherical mirror. We design the metasurface using dielectric nanofins that act as half-wave plates in reflection. In our design, we consider the coupling between building blocks using full-wave numerical simulations of the entire metasurface structure. By properly choosing the orientation of each and every nanofin, the

Figure 1: Concept and simulation of the reflective metasurface. (a) Gaussian reflective metasurface reflecting a Gaussian beam back onto itself. (b)-(g) Incident and reflected beams of the hybrid Gaussian retroreflector built with TiO2 nanofins on top of an Al substrate, optimized for a wavelength $\lambda = 1064$ nm with unit cell size $P = 380$ nm. This mirror has a radius of 12.57 $\mu$m and a focal length $f = 50\lambda$. Top row: (a) Intensity distribution of the incident Gaussian field ($I_i$) as a function of the distance $z$ from the metamirror; (b) beam profile at $z = 1350$ nm; (c) beam profile at the focal point $z = 50\lambda$. Bottom row: (d) Intensity distribution of the cross-polarized reflected beam ($I_c$) as a function of the distance $z$ from the metamirror; (e) beam profile at $z = 1350$ nm; (f) beam profile at the focal point $z = 50\lambda$. 
designed mirror can refocus a Gaussian beam down to a distance of 50 times the wavelength of light. This metasurface can produce a reflected cross-polarized beam that perfectly overlaps with the incident field [see Fig. 1(b)-(g)]. Our optimized designs, using TiO2 nanofins as metasurface building blocks placed on an Al back mirror, have efficiencies over 90%. These metasurfaces exhibit minimal losses, together with a homogeneous and complete phase coverage.

The proposed reflective metasurface may be suitable for applications as diverse as optical tweezing, lasing, and quantum optics. For example, it could be utilized to build ultracompact reflective mirrors or confocal microcavities that could be implemented in the design of optical tweezers and other nanophotonic devices.

3. Large-Scale Metasurfaces

We will also discuss a novel, facile methodology to construct phase gradient metasurfaces from an exposed standard electron beam resist. The method dramatically cuts the processing time often required to build metasurfaces and also reduces safety hazards. We will demonstrate the advantages of this fabrication method by showing results of high-performance flat optics components based on the Panchanaram-Berry phase gradient concept. Our manufactured devices include lenses, gratings, exhibiting anomalous reflection, and cylindrical metalenses on flexible plastic substrates. The resulting metasurfaces are efficient (polarization conversion >50%), function across the entire visible wavelength spectrum, and have a large area (1 cm in diameter). The method is also compatible with a wide range of substrates—we will show examples of metasurfaces on both flexible plastic supports and metallic mirrors. This may open new avenues for combining flexible electronics with flat optical devices.

Acknowledgements

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References

Optimization Paradigms for Metasurface Inverse-design

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Abstract
Metasurfaces with high efficiency and broadband performance hold the potential to revolutionize optical system design. However, advanced optimization methods and design techniques must be exploited to achieve performances that surpass conventional optical systems. In this paper, two metasurface design strategies are presented and their advantages and challenges discussed. The first strategy is based on topology optimization while the second is based on deep learning. Finally, we discuss how hybridizing these techniques could surpass the state-of-the-art for metasurface optimization.

1. Introduction
Metasurfaces hold the potential to reduce the weight and size over more conventional optical systems [1]. However, to be viable alternatives, metasurface focusing devices and predict their performance. This has led to better freeform designs [14], and even to the explanation of underlying physics [15] governing these devices. Thus, optimization and machine learning are playing a critical role in achieving next generation metasurface devices. This paper provides a brief introduction to topology optimization and deep neural networks and concludes with an outlook on hybridizing these techniques.

2. Metasurface Design
Topology optimization is an extremely powerful design approach because it can generate gradients for a nearly limitless number of variables with only two full-wave simulations. The drawback of this method is that designs can get trapped in suboptimal local minimas. This can sometimes be mitigated by starting multiple optimizations at various initial points in the design space. In conventional applications of topology optimization, designs are initialized as a gradient-index (GRIN) slab whose permittivity varies across the structure (see Fig. 1). The structure is then pixelized and

![Figure 1: Method for designing topology optimized structures. The design domain is initially seeded with a random refractive index profile. Using only two simulations the gradient for how to change the refractive index at every location can be calculated. Over the course of the optimization, the refractive index is changed to obtain steady improvements in transmission efficiency while simultaneously forcing the design to become two discrete materials with either the max or min refractive index.](image-url)
the permittivity in each pixel is updated by the gradient calculated at its location in order to improve efficiency. Over the course of the optimization the permittivities are slowly coerced to either the max or min value resulting in a final structure that is completely binary (see Fig. 1) and can be fabricated. However, discretizing the design over the course of the optimization can lead to it getting stuck in local minima which necessitates the need for multiple optimization trials to find a suitable final design. Furthermore, for multiple design objectives (such as broadband performance) the gradients for each objective might be in competition with one another. This makes it more difficult to find broadband or multifunctional devices without many simulations, because it is very difficult to choose the optimal weights between the multiple gradients. However, many simulations can be useful for training deep neural networks.

Another interesting area of research that can vastly improve metasurface design is machine learning, specifically deep neural networks. When the optimization process produces a vast number of designs with corresponding performance metrics, it is possible to train a neural network to accurately predict performance metrics for a freeform metasurface. Once the neural network is properly trained, it can be evaluated nearly instantaneously in order to quickly explore the design space. Figure 2 shows a depiction of a deep neural network where the transmission profile of a metasurface is the result of input data being propagated through the multilayer structure according to the different weightings between neurons.

Figure 2: A deep neural network showing the multilayer structure with different connections having different weights in order accurately predict the transmission profile of a design.

## 3. Conclusions

Topology optimization and machine learning are revolutionizing metasurface design, because of their ability to handle many input variables. This flexibility allows for freeform structures that significantly outperform more conventional design approaches. Our presentation will discuss work on using topology optimization to create unit cells with arbitrary phase and to design geometric phase-based unit cells. Furthermore, we are investigating using deep neural networks to accurately predict freeform unit cell performance, which then can be used in a variety of applications such as designing for robust structures that are less sensitive to fabrication imperfections.

### Acknowledgements

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Contour integral methods for resonance phenomena in nano-optics

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Abstract

We review contour integral methods for the solution of nonlinear eigenvalue problems resulting from Maxwell’s equations. Numerical realizations of the methods are applied to compute and analyze resonances in nano-optical systems with material dispersion.

Riesz projections for solving nonlinear eigenvalue problems

A comprehensive knowledge on the resonances occurring in nano-optical systems is essential for understanding their physical properties and for designing and optimizing related devices. Nonlinear eigenvalue problems resulting from Maxwell’s equations for the electromagnetic field can be solved numerically in order to analyze the resonance phenomena [1]. Material dispersion causes the nonlinearity of the eigenvalue problems and is often described by the Drude-Lorentz model or rational fits to measured material data [2, 3]. The computation of the eigensolutions, so-called quasinormal modes (QNMs), and the modal expansion of the electromagnetic field into a weighted sum of QNMs are challenging tasks in computational nano-optics [4].

Contour integrals methods [5, 6, 7] can be applied to solve nonlinear eigenvalue problems [8]. These methods have become popular in recent years and are well suited for Maxwell’s equations. They construct an approximate subspace corresponding to specific QNMs whose eigenfrequencies are located inside a chosen region in the complex frequency plane.

In this contribution, we review contour integral methods for the investigation and optimization of light-matter interaction in resonating nanostructures. The methods are based on a finite element implementation for the time-harmonic Maxwell’s equations. In particular, we report on approaches based on Riesz projections [9, 10, 11]. The approaches can be applied to systems described by any material dispersion relation. They allow for computing specific physically relevant eigensolutions [10] and modal expansions of quadratic quantities with a sesquilinear map, such as the electromagnetic absorption and the far-field electromagnetic energy flux [11, 12].

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References

Thermal Plasmonics and Metamaterials for Environment and Energy Application
Titanium nitride and silicon nanostructures for photothermal applications [Invited]

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Abstract

We report photothermal conversion of high aspect ratio TiN and Si nanostructures. We fabricate two types of TiN nanostructures: trenches and tubes, and two types of Si nanostructures: trench and air hole arrays in Si. We study the photothermal properties of these nanostructures by measuring Raman shift of the materials that corresponds to the temperature in terms of laser power. These high aspect ratio nanostructures exhibit significant temperature increase, showing the potential for highly efficient photothermal converters.

1. Introduction

Metallic nanostructures support localized surface plasmon polaritons that tightly confine electric fields and subsequently generate heat, which leads to photothermal applications, such as optofluidics, enhancement of chemical reactions [1]. While gold has been extensively used as plasmonic materials with negative permittivity, recently titanium nitride (TiN), a refractory metal that exhibits plasmonic response in the visible and near-infrared wavelengths, has been emerging as an alternative plasmonic material [2]. TiN is more abundant than Au and has the high melting point, which is in particular advantageous for thermal applications. Up to present, TiN nanoparticles and nanostructures have been studied for photothermal applications [3, 4]. Apart from plasmonic nanostructures, Si exhibits absorption in visible and near-infrared wavelength below 1.1 μm. We also explore the potential of photothermal properties of high aspect ratio Si nanostructures.

2. Experimental Results

High aspect ratio titanium nitride (TiN) nanostructures are fabricated by the combination of deep-UV (DUV) lithography, deep reactive ion etching (DRIE), and atomic layer deposition (ALD) techniques [5]. Similarly Si trench and air hole array in square lattice are also fabricated by DUV lithograph and DRIE as templates for TiN structures. Such
high aspect ratio trench, pillar, and tube nanostructures can be fabricated with various choice of materials [6, 7, 8] and lead to applications, such as, sensing [5, 9]. All of fabricated nanostructures have the pitch of 400 nm. The fabricated TiN nanotrench structures have 2.7 μm height while TiN nanotubes have 2.0 μm height on Si substrate as shown in Fig. 1. Si trench structures have the height of 3.0 μm, while air hole arrays in Si have the height of 2.0 μm.

First we measure the Stokes peaks of the 150 nm thick TiN film deposited on a Si substrate by ALD with a heater underneath that provides various temperatures. In this manner, we obtain the Raman shift of TiN in terms of temperature as our reference. Then, we shine laser with 785 nm in wavelength to each of nanostructure samples and measure the temperature rise via Raman shift in terms of laser power. We find significant temperature rise compared with TiN nanostructures with low height of 160 nm [4]. Moreover, as show in Fig. 2, TiN nanotube structures in air becomes oxidized over 1 mW of laser power. Even though TiN nanotubes are covered by Al₂O₃ layers that prevent oxidation, they also become oxidized for 5 mW of laser power. Submerged in water, both TiN structures are oxidized by 15 mW of laser radiation. For TiN film deposited on Si substrate, the oxidation power is over 30 mW in water.

We also conduct the same study for Si trenches and air hole arrays in Si. Here we conduct a laser with the wavelength of 532 nm. We observe significant temperature increase for Si trenches, up to 150 °C while flat Si substrate does not show large temperature rise. This shows that even though Si is not plasmonic for visible to near-infrared wavelength, efficient photothermal conversion can take place when Si is nanostructured.

3. Conclusions

Our study shows that when both TiN and Si are structured in high aspect ratio (5 - 7 times of their pitch), lower laser power is required for heating and oxidation. It also suggests that such high aspect ratio plasmonic TiN and dielectric Si nanostructures can be an efficient photothermal converter for the visible and near-infrared wavelengths for various applications.

Acknowledgement

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References

Waveguiding of Radiation from Silica Plates

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Abstract

In these years, a number of studies have reported on passive radiative cooling (RC), because it refrigerates objects, such as solar panels, without using electricity. The RC occurs, stemming from blackbody radiation to low temperature medium or the universe. In this paper, improvement of RC ability of a silica plate with silica particles is demonstrated. This is due to the decrease in the reflectivity at the flat surface of a silica plate at the mid-infrared wavelength range. It is also shown that handling of RC is possible using aluminum waveguide. This expands the possibilities of the method for various applications.

1. Introduction

In these a few years, a number of studies have reported on passive radiative cooling (RC), because it refrigerates objects such as solar panels without using electricity[1]. As shown in Fig. 1, RC occurs stemming from blackbody radiation to low temperature medium or the universe. The blackbody radiation at room temperature has a broad emission band at around 10 µm, and the infrared band is overlapped with the atmospheric window. Therefore, the materials with high absorption efficiency at these wavelengths are required to realize the PRC devices. Silica (SiO$_2$) is one of the suitable materials for RC, because the surface phonon polariton band exists at the infrared wavelengths. However, it does not have perfect absorption because of the low real-part refractive index less than unity, which leads to increase in reflection.

In this paper, I will show improvement of RC from silica plate using silica particles. The reflection is suppressed by the particles, resulting in the increase in the emission. I will also report waveguiding of the infrared emission. It is found that the refrigeration can be made through the waveguide. This expands the possibilities of the method for various applications.

2. Results and Discussion

Figure 1 shows the temperature difference of the silica plates with and without particles, when the silica plates are exposed to liquid nitrogen (LN). Although LN has no absorption (emission), the surface of the vessel is a glass that has absorption at the mid-infrared range. The presence of particles at the silica plates promotes the RC performance.

Table 1: Temperature decrease of different waveguides.

<table>
<thead>
<tr>
<th>Waveguide</th>
<th>L-type</th>
<th>Z-type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L = 0.75$ m</td>
<td>$6.4$ K</td>
<td>$3.9$ K</td>
</tr>
<tr>
<td>$L = 1$ m</td>
<td>$4.6$ K</td>
<td></td>
</tr>
<tr>
<td>$L = 1.25$ m</td>
<td></td>
<td>$4.0$ K</td>
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</table>
Figure 3 shows the geometry of RC waveguiding. Two types of waveguides, L- and Z- types, were prepared. In L-type, the length can be changed. The cross-section of the waveguide is a rectangle (5 × 12 cm). Inside the waveguide is coated with an aluminum film. The decrease in temperature $\Delta T$ for various waveguides are summarized in Table I. The RC can be made through the waveguide. Although $\Delta T$ decreases with the length $L$, the decrease is small, and we can use the waveguide for RC.

2.1. Conclusion

Improvement of RC ability of a silica plate with silica particle is demonstrated. This is due to the decrease in the reflectivity at the flat surface of a silica plate. It is also shown that handling of RC is possible using aluminum waveguide. This expands the possibilities of the method for various applications.

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References

Smart Meta-optical Solar Reflector based on Vanadium Dioxide

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Abstract

Optical solar reflectors (OSRs) play a crucial role in the thermal control of a spacecraft. We present novel ‘smart’ metasurface-based OSRs using vanadium dioxide (VO2), which has its infrared emittance modulated with temperature through the thermochromic characteristics of the VO2. We have investigated the infrared property of the ALD VO2 films under different anneal conditions and found the anneal condition can optimize VO2 infrared response. We have demonstrated that a superior emittance tunability and lower solar absorption for meta-OSRs than the planar film device.

Keywords: meta-surface, radiative cooling, perfect absorption, plasmonics, optical solar reflectors, vanadium oxide.

1. Introduction

Optical solar reflectors (OSRs) [1] play a crucial role in the thermal control of spacecrafts since they are the physical interface between the thermal management system and the space environment. To avoid solar heating and adopt radiative cooling, an ideal OSR is required to reflect all energies in the UV/Vis/NIR spectrum and emit the thermal infrared (IR) spectrum (blackbody radiation spectrum). To maintain the temperature under different operational conditions, e.g. eclipse, the thermal emittance would be desired to be tunable and this function is currently achieved by an active system involving electronic sensing and control systems with complicated mechanical parts. Therefore, there is a need for a thin-film technology-based passive control system having a low emittance at low temperature and high emittance at high temperature.

Recently, vanadium oxide (VO2) becomes popular for its thermochromic property. VO2 is dielectric below its transition temperature and metallic above the transition temperature and therefore forms a smart meta-OSR with a tunability against temperature change [1]. In this work, we report the results of H2020 Meta-reflector and Smart-Flex projects on a smart Meta-OSR based on VO2.

2. Results and Discussions

The proposed structure is a traditional Salisbury screen consisting of a stack of three layers: the metal back reflector, the dielectric spacer layer and the VO2 meta-surface [2] [3]. The performance of an OSR is defined by its solar spectrum absorption (α) and infrared spectrum emittance at 300 K (ε). The emittance, ε, is defined as the averaging emissivity weighted by the theoretical blackbody spectrum at the operating temperature (T) in Kelvin:

\[ \varepsilon = \frac{\int_{\lambda}^{\infty} B(\lambda, T) \varepsilon(\lambda, T) d\lambda}{\int_{\lambda}^{\infty} B(\lambda, T) d\lambda} \]  

where \( \lambda \) is the thermal conductivity, \( B(\lambda, T) \) is the blackbody spectral distribution at temperature T, given by Plank’s equation. For smart OSRs, the emittance tunability (Δε) is the figure-of-merit, which is the emittance difference at high and low temperatures.

2.1. VO2 and W-doped VO2 by Atomic layer deposition

In this work, we have formed VO2 using atomic layer deposition (ALD) technique based on TEMAV and water. The ALD technique is highly advantageous for its film uniformity (up to 300 mm diameter) and fine thickness control. Figure 1a shows Raman spectra of the formed VO2 after different anneal treatments, which recrystallized the VO2 into the desired crystalline phase, VO2(M). The color lines are the known peaks for VO2 film in the literature. Raman spectra show VO2 films after all treatments are dominant VO2(M). Figure 1b shows IR absorption spectra of VO2 planar OSRs by different anneal conditions. The
450°C anneal offers a significant lower IR absorptions than the 425 °C anneal. This result indicates that the VO₂ IR response depends on its anneal condition, though the Raman spectroscopy show little difference among these films. Thus, a material optimizations is needed for the IR applications. The emissivity is extracted and plotted as a function of temperature (Figure 1c). This gives a delta emissivity of 0.55. The deposited film thickness mapping (Figure 1d) shows an excellent VO₂ uniformity of less than 2%, making it suitable for scale up manufacture.

2.2. VO₂-based smart OSRs

Figure 2a shows the UV/VIS and FTIR absorption spectra of a VO₂-based smart meta-OSR with an array of VO₂ squares of 2.4 µm and a gap of 0.5 µm measured at 25°C and 80°C. The infrared absorption is significantly increased when temperature is increased to 80°C. Figure 2b shows extracted Δε as a function of square size at different gaps. Meta-OSRs for all feature size with a gap of 0.5 µm achieve higher Δε than planar film, whilst the Δε improvement decreases with the increase of gap size and even below the planar film. This is attributed to the reduction of VO₂ filling ratio of the whole surface. The best smart-OSR gives an emittance tunability improvement by 30%. In addition, the reduction of VO₂ coverage would positively contribute to a lower solar absorption.

Figure 2: (a) UV/Vis/Infrared absorption spectra of a VO₂ smart meta-OSR with a feature size of 2.4 um and gap of 0.5 um measured at 25 and 80°C, (b) emittance tunability as a function of feature size at different gaps and (c) smart OSRs fabricated on flexible Ti foil.

3. Conclusions

We report vanadium dioxide based smart meta-OSRs for space applications. The IR response of VO₂ can be optimized through post anneal treatment. The fabricated VO₂ smart meta-OSR show a superior emittance tunability improvement by up to 30%. The smart meta-OSRs has been demonstrated to be able for scaling up to large area flexible substrate through nanoimprint or standard photolithography. Comprehensive robust tests have been performed to test their durability at harsh space environment.

Acknowledgements

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Complex metamaterials for energy applications

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Abstract
In this invited talk I will summarize recent research of my group on complex metamaterials for various energy and environmental applications ranging from world record water splitting, photo-catalysis, solar desalination and structural coloration.

1. Introduction
Billions of years of natural evolution have resulted into a multitude of multicellular organisms, which routinely use optimized nanostructures to perform complex operations. Although the working principle of these systems is still unclear, their common denominator is the presence of many interacting and fully heterogeneous units. The neural network of the brain is composed of 100 billions of neurons, and does not contain two identical cells. The same complexity is observed in unpredictable phenomena such as hurricane, tornadoes and anomalous water waves, which are observed in environments that are normally in a quiet state. An intriguing question is whether is possible to embed the complex character of these systems into a new generation of high performing devices for different applications. If this possibility could be opened, we would be able to have at disposal an extremely powerful engineering technology whose performances, scalability and sustainability are orders of magnitude higher than our current systems. In this invited talk we will summarize the recent research results obtained by our group in the development of complex materials for energy harvesting applications that are characterized by zero carbon emission. We begin by discussing the design and fabrication of an ultra-dark biomimetic materials made of nanoparticles that are inspired by a camouflage technique of an Asian specie of beetles living in the south east Asia, and their application for solar steam production and water desalination with a record of efficiency. We will then discuss a new path in nanomaterial engineering inspired from a dynamical camoufage of a family of coleid cephalopods, and its application to photovoltaics and photocatalysis cells for the generation of hydrogen and chemical fuel feedstocks with a word record of efficiency [1, 2, 3, 4, 5].

References

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Titanium nitride for light-to-heat and heat-to-light conversions

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Abstract
Metallic properties of titanium nitride (TiN) can be used to enhance non-radiative decay processes in the nanoscale. In the current paper, our recent works using TiN nanostructures for photothermal heating and wavelength-selective thermal emissions are reviewed.

The carrier concentration of titanium nitride (TiN) is high enough to excite surface plasmon resonance even in the visible range. During the past several years in particular, there have been numerous works on studying the radiative properties of TiN such as exciting propagating of localized plasmon resonances and efforts have been made to decrease the optical absorption of TiN [1]. Despite all these studies the metallic property of TiN is still inferior to gold or silver. However, for applications making use of non-radiative decay processes, TiN can be a material of choice [2]. The optical losses of TiN are not too large such that it is possible to enhance optical absorption in a broad spectral range from visible to near infrared (NIR). In addition, TiN can be used for wavelength selective thermal emitter in the mid infrared (MIR) range. In the following, we review our recent works on photothermal heating and thermal emission using TiN (Figure 1).

During the past five years, we have worked on photothermal heating using TiN nanostructures. In the form of nanoparticles, absorption efficiencies of TiN nanoparticles exceed unity from visible to NIR which cover most of the solar spectra [3]. Thus, TiN nanostructures can be efficient sunlight absorbers. After the initial demonstration of solar heater evaporation by TiN nanoparticles, we extended our work to increase the evaporation efficiency. The second generation of our structure is based on ceramic wool where TiN nanoparticles were chemically bonded to the ceramic wool [4]. With this structure, capillary force was utilized to increase the efficiency up to ~45%. In the third generation, porous alumina was used as a template and TiN was coated on the top [5]. With a structure to float the TiN-coated porous alumina, the evaporation efficiency increased up to 92%. This is one of the highest efficiencies that ever reported, however, there are many other structures which demonstrated above 90% efficiency and some of them have demonstrated above 100% efficiency [6]. One of the applications of solar water evaporation is desalination of sea water. With this regard, it is important to bear in mind that photovoltaic reverse osmosis desalination has orders of magnitude higher efficiency that solar-thermal desalination using the sample presented earlier [7]. As such, solar-thermal desalination should stress proper merits such as portability, simplicity and low cost in practical applications.

In photothermal heating of water, it is of interest to know the water temperature adjacent to TiN nanostructures. To this end, we performed Raman spectroscopy to measure the water temperature above the TiN nanostructure which was fixed to a substrate and irradiated by a laser. Our study revealed that a temperature plateau region appeared in the super-heated phase of water which could be a unique feature of optical heating [8].

In addition to water evaporation applications, solar heat generated by TiN nanostructures can be used for sunlight-responsive shape memory [9] and oxidation of carbon monoxide [10].

Optical absorbptivity is direct related to emissivity following the Kirchhoff’s law or thermal radiation. Thus, TiN can be a thermal emitter and the wavelength dependent thermal emission can be tuned by structuring TiN nanostructures. In our work, we designed multilayers consisted of a TiN film and a distributed Bragg reflector to excite Tamm plamon polaritons [11]. This structure was able to demonstrate wavelength-selecive thermal emission in MIR having the Q-factor of 6.6 which is comparable to other metamaterial thermal emitters.
Figure 1. Schematic of photothermal heating and thermal emission by TiN nanostructures

Acknowledgements

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References

Heat transfer regulation for textiles using tailorable metallic wires

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Abstract
We numerically explore the concept of dynamic, switchable infrared transmittance using electromagnetic and thermal calculations, for the use of smart, temperature regulating textiles. We discuss the photonic effects of metallic and shape-memory-polymer coated mono-filaments on the temperature dependent transmittance of the textile fabric

1. Introduction

Passive personal thermal management using smart textiles, which could provide localized thermal regulation, has become a center of attention. This nano- and micro-photonics driven technology is regarded as an efficient strategy to facilitate efficient thermal comfort and personal health. It is also considered as a potential solution to meet climate control targets, and move towards a low carbon economy, by decreasing the energy cost for heating and cooling.

At a normal skin temperature of 34 °C, our skin emits Infrared Radiation (IR) with peak wavelength around 9.5 μm, and this IR heat dissipation contributes to more than 50% of the total body heat loss in indoor environments. Therefore, with proper photonic IR management, one can tailor and design passive temperature regulating textiles. Currently, a few types of such fabrics have been proposed and developed for cooling purposes [1], for heating purposes [2], and for both functionalities at once [3]. However, there is a long way to go when it comes to a perfect dynamically operating passive temperature regulating textile fabric.

In this work, we present a Dynamic Transmissivity Switch Textile (DTST) technology, a novel approach for a dynamic temperature regulating textile fabric that allows controlling the IR transmission by adapting to the ambient temperature and humidity. The IR transmissivity switch-based fabric allows us to control the thermal heat transfer between the human body and the ambient. We perform an extensive numerical study of the photonic properties of the proposed design geometry. These electromagnetic simulation results allow one to determine optimized geometric parameters that correspond to heating and cooling functionality.

2. Design working principle

The DTST has two operation modes: the heating mode for a warming functionality, and the cooling mode for a cooling functionality (see Fig. 1). The two modes coexist in one fabric simultaneously. Meanwhile, there is a passive switching mechanism that allows switching from one mode to the other. Here, shape memory polymer beads are proposed as a driving force for passive switching. Recent studies have reported that polymers such as bio-based polylactide-urethane and polyurethane show shape memory properties around the human body temperature [4].

For example, at a predetermined comfort zone temperature below a critical temperature \( T_c \), the polymer beads keep a particular geometry. When the temperature rises above \( T_c \), the polymer beads expand, thus increasing the separation distance \( d \) between two consecutive mono-filaments. This results in a new geometric configuration with an expected increased IR transmissivity. On the other hand, when the ambient temperature drops below \( T_c \), the polymer beads shrink, thus decreasing \( d \). As a result, the initial geometric configuration will change, and the IR transmissivity decreases.

Figure 1: Schematic illustration of DTST and the working principle: (i) Heating mode and (ii) cooling mode.
To study the IR transmission of the proposed textile design, we employed a numerical finite-element method simulation using COMSOL Multiphysics v5.3. Figure 2 illustrates the numerically calculated spectral transmittance as a function of wavelength for a fixed filling factor $f_f = 0.15$ and varying $d = 4, 10, \text{and } 12 \mu\text{m}$. It also shows the spectral emissivity of the human body at $34 ^\circ \text{C}$ skin temperature (dashed curve).

From Fig. 2, one observes that the spectral transmittance curves behave differently in several wavelength regions due to various photonic effects. It is possible to study these effects by choosing one spectral curve, for example, $d = 10 \mu\text{m}$ (orange). For the larger wavelength region starting from a cut-off wavelength of $18 \mu\text{m}$, it exhibits a wide stopband, called the plasmonic gap. Interestingly, this gap does not originate from the geometry of the design, rather from the physical property of the metal wires. Consequently, right below the plasmonic gap, there exists a first transmission band that extends from $12$ to $17 \mu\text{m}$. Furthermore, the three resonance transmission peaks present in the first transmission band are due to a Fabry-Pérot type cavity effect. Due to the geometric design, there exists a structural ‘photonic’ bandgap below the first transmission band extending from about $9$ to $12 \mu\text{m}$. And finally, there is a second transmission band below $9 \mu\text{m}$.

The above photonic effects are present in all spectral curves, so we can assess the influence of changing $d$ in the process of IR transmittance. When $d$ increases, the spectral curve shifts to a longer wavelength region and, when $d$ decreases, to a shorter wavelength region. With this shift, one thus shifts the plasmonic gap, the first transmission band, and the structural bandgap. As a result, for larger $d$ (but not too large), the transmission band is underneath the maximum of the human body emissivity curve, leading to more transmission of IR thermal radiation from the skin to the environment. This allows DTST to operate in the cooling mode. On the other hand, for smaller $d$, the plasmonic gap is underneath the human body emissivity curve. Consequently, very low IR thermal radiative transfer from skin to the environment is realized; in this case, DTST is operating in the heating mode.

In order to assess the thermal performance, we performed one-dimensional steady-state heat transfer calculations. In the thermal calculations, one considers a constant body heat generation of $Q = 70 \text{ W/m}^2$ for a sedentary individual with a skin temperature of $34 ^\circ \text{C}$. We assume a typical air gap of $1 \text{ mm}$ for the microclimate thickness. This calculation gives the environmental setpoint temperature (the temperature at which a sedentary individual remains comfortable). The typical natural setpoint temperature window for human comfort in office seating is $2 ^\circ \text{C}$ (21-23 °C). With DTST one is allowed a much larger $\sim 16 ^\circ \text{C}$ temperate window, as this textile can provide a thermal comfort with the lowest setpoint at $9.5 ^\circ \text{C}$ and the highest setpoint at $25.7 ^\circ \text{C}$.

### 3. Conclusions

In this work we demonstrate a personal radiative temperature regulating fabric based on a Dynamic Transmissivity Switch Textile (DTST). The proposed design is constituted from metal-coated mono-filaments and shape-memory-polymers beads, which enable the design to interact more effectively with IR radiation and to respond in a dynamic manner. Furthermore, the design benefits from various IR photonic effects to control the transmission of thermal radiation, and provides a suitable thermal comfort for users. Numerical calculations show a promising possibility of exploiting these photonic geometries for tailoring the IR transmittance from the human body to the environment. DTST possesses a $\sim 16 ^\circ \text{C}$ ambient temperate window, which is by far the largest setpoint window reported.

### Acknowledgement

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### References


Omnidirectional Narrow-band Thermal Radiation by Mie Resonator on Refractory Metal

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Abstract
We propose a narrow-band thermal radiation emitter based on a refractory metasurface composed of Germanium Mie resonators on Tungsten substrate. The metasurface radiates omnidirectional thermal radiation with a quality-value $Q$ of 132 and an emissivity of 0.96 at mid-IR range in simulation. We fabricated the device and demonstrated $Q$=34 at 7.8\,µm in experiment.

1. Introduction
Recent progress of metasurface realizes narrow-band absorption/emission by Metal-Dielectric-Metal (MDM) plasmonic resonators. For instance, perfect emitter for gas sensing [1] or vivid plasmonic color printing [2] are demonstrated by MDM-based metasurface. Recently, we demonstrated a thermal radiation emitter made of refractory metasurface based on Hafnium Nitride (HfN) with a melting point of 3603\,K [3]. However, its quality-values $Q$ of typical plasmonic resonators are limited to 1–10, which is not sufficient for a thermal emitter for gas sensing applications. In order to increase $Q$-value significantly, we propose a new kind of structure based on high refractive Mie resonators here.

In this study, we experimentally demonstrate a narrowband thermal emitter in mid–IR (infrared) range by Germanium (Ge) Mie resonator on Tungsten (W) substrate. The device shows omnidirectional thermal radiation with $Q$=132 and emissivity $\varepsilon$=0.96 in simulations.

2. Mie resonator on refractory metal
Figure 1 shows schematic and cross-sectional view of the metasurface composed of cylindrical Ge Mie resonators on a W substrate (Ge-W structure) with a thin Al$_2$O$_3$ layer. We calculated absorptivity spectra of the metasurface by FDTD simulation. We also calculated electromagnetic filed around the meta-atom.

Regarding to sample fabrication, at first Ge and Al$_2$O$_3$ film were deposited onto W substrate by RF sputter. Then, we fabricated the metasurface by conventional electron beam (EB) lithography and dry etching process.

We measured absorptivity and thermal radiation spectra by FTIR. The mid-IR radiation spectra were measured at the temperature of 373\,K in a vacuum chamber (2 x $10^2$ \,Pa) connected to the FTIR in incident angle perpendicular to the substrate. Here, the sample was set on and heated by a ceramic heater.

Figure 1: A schematic and cross-sectional view of Ge Mie resonators on W with an Al$_2$O$_3$ gap layer.

3. Results and discussions
Figure 2 shows calculated absorptivity of the Ge-W structure. We also plot blackbody spectrum at 373\,K as a reference. From the simulation, we found that a magnetic dipole (MD) was dominant in radiation and its resonant peak was observed at 7.8 \,µm with $\varepsilon$=0.96 and $Q$=132, which is greater than that of the MDM [1,3]. We also observed that background emissivity took $\varepsilon$=0.1 out of the resonance. Such results suggest that we can expect to suppress unnecessary thermal radiation significantly. In the experiment, we obtained $\varepsilon$=0.84 and $Q$=34 at 7.8\,µm. We will discuss about the difference between simulation and experiment in detail.

Figure 2: Calculated thermal radiation spectra of Ge-W structure (red dotted line) and blackbody at 373\,K (dotted line).
Acknowledgements

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References


A Suspended TiN Film for Thermal Plasmonics Platform

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Abstract
In this study, a suspended TiN film on a silicon substrate is studied and fabricated through sputter deposition and sacrificial layer etching. The balance of the internal stresses between TiN and sacrificial layers are found to be important to release suspended film structures. Modification of spectral reflectance was demonstrated by introducing hole array structure to the suspended film.

1. Introduction
Spectral selective emitter is one of the promising applications of plasmonics, and used for gas sensing, thermophotovoltaic power conversion, and so on. However, poor heat resistant properties of plasmonic noble metals (Au, and Ag) have prevented extension of applications. TiN is expected as an alternative plasmonic material, especially in the raised temperature range. In order to increase temperature effectively, free-standing, or suspended structure is important to minimize both heat capacity and heat losses due to conduction and convection. In this study, fabrication of suspended TiN film was demonstrated, and modification of spectral reflectance based on plasmonic hole array is reported.

2. Experimental

2.1. Device Design and Fabrication

Figure 1 shows schematic illustration of proposed device. A TiN film is deposited on a SiO2 insulator and suspended above the Si counter electrode for thermal insulation. TiN film can be heated up by applying current between TiN electrodes across suspended part. On a suspended TiN film, periodic hole array is formed in order to both etch substrate silicon layer and have plasmonic response in its emissivity spectrum. Hole pitch p and diameter d were used as parameters.

Figure 2 shows schematic illustration of fabrication process. A 2-cm-square silicon chip was used as a starting material. SiO2 films with the thickness of 700 nm are thermally grown at 1100°C for 1 h (a). The top SiO2 film was patterned using photolithography (b) and wet etching using buffered hydrofluoric acid (c). In this step, backside SiO2 film was also removed. And then resist mask was removed (d), TiN pattern was formed by photolithography (e), TiN sputter deposition (f), and lift-off (g). At the step (f), a sputtering apparatus SH-450 (Ulvac Co.) was used. A 500-nm-thick TiN film was deposited by dc sputtering with the power of 500 W for 120 min using TiN target. Finally, suspended
2.2. Results and Discussion

Fig. 3 shows SEM images of the fabricated suspended TiN film. Both the length and width of suspended TiN films were 500 µm. Residual stress control is essential to successfully release the suspended film structure. Fig. 4 shows cross sectional profiles of Si substrates whose thermal SiO₂ (700 nm) and TiN (400 or 500 nm) were deposited. In contrast to thermal SiO₂ has strong compressive stress, sputter-deposited TiN has tensile stress. As a result, the total residual stress decreased from 163 to 76.3 MPa when the TiN thickness was increased from 400 to 500 nm. However, if the TiN layer become much thicker, it may brittle due to its strong tensile stress.

Fig. 5 shows measured Fourier-transform infrared (FT-IR) spectra of the suspended TiN films with parameters of \( p = 10 \mu \text{m}, d = 5 \mu \text{m}, \) and \( p = 13 \mu \text{m}, d = 7.5 \mu \text{m} \). Relative reflectance were calculated using the non-suspended region of TiN film (side part of Fig. 3 left) as the optical reference. As shown in Fig. 5, both samples shows structural reflectance dips, which correspond to high absorbance and spectral emissivity. The latter sample shows deeper dip and longer resonant wavelength. As shown in this result, spectral modification was achieved with suspended TiN film structure.

3. Conclusions

A suspended TiN film on Silicon substrate are studied and fabricated through sputter deposition and sacrificial layer etching. The balance of the internal stresses between TiN and sacrificial layers are found to be important to release suspended TiN film. Modification of spectral reflectance was achieved through changing the pitch and diameter of hole array on the TiN film. This structure is expected as a thermal plasmonics platform.

Acknowledgements

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References


A transparent fluoropolymer for daytime radiative cooling

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Abstract

While a passive radiative cooling technology actives well during the nighttime, the peak cooling demand actually occurs during the daytime thus it is essential to find daytime radiative cooling materials. We introduce the fluoropolymer film that is transparent 98% of incident sunlight and emitting 97% in the atmospheric transparency window. By the indoor experiment, the 50 µm-thick fluoropolymer film cools to 7.6 °C below ambient air temperature. Moreover, the paint-ability and the weather-resistant allow to apply the fluoropolymer film in the wide range of human life.

1. Introduction

Today, air conditioning consumes about 15% of the global energy and the figure is predicted to triple by 2050 [1]. Thus, reducing current energy consumption and improving energy efficiency are important. Passive radiative cooling (RC) that cools with no electrical power therefore has a significant impact on energy sustainability [3]. The Earth’s atmosphere is transparent for electromagnetic waves at 8-13 µm, which called atmospheric transmission window (ATW). Especially, ATW coincides with peak emission of black-body at average ambient temperature. Thus, any sky-faced objects with high emissivity in the ATW can radiate heat to the universe (3K).

To achieve daytime RC, the device must satisfy following conditions: (1) transparent in visible region to minimize absorbed power, (2) high emission in ATW to maximize radiated power. In previous studies, the advanced photonic structures with selective emission spectra were reported while they suffer from high fabrication costs and problem with large areas [3, 4, 5]. In this study, we confirm the RC efficiency of the fluoropolymer (LUMIFLON™, solvent-soluble fluoroethylene and vinyl ether (FEVE) resins) film and compared with that of various materials: polydimethylsiloxane (PDMS) [2], polyethylene (PE) films, a soda-lime glass and a soda-lime glass with silica particles (φ = 20 µm). The fluoropolymer film has a weather-resistant and a paint-ability, thus promises for coating buildings, vehicles or solar cells.

2. Passive radiative cooling material

The soda-lime glass coated both sides by 100-nm thick gold film was supported as a substrate. The gold film expresses the low RC performance to avoid the RC from the soda-lime glass. The drop casting method was used to propose the fluoropolymer film on the substrate. The various thickness is obtained by controlling the volume of a solution. The ease of manufacturing method allows to overcome the barrier of implementation.

For 50 µm-thick fluoropolymer film, the optical absorption in visible regime is weak (yellow area of Fig 1). According Kirchhoff’s law, the absorption of emitter is equal its emissivity. In the ATW, the absorption/emissivity is strong and close to unity due to the vibration of CF3 and CF2 stretch at 1350-1120 cm−1 and 1280-1120 cm−1, respectively (pink area of Fig 1). Especially, the emission peak coincides with a peak of black-body radiation thus it promises for high heat dissipation to the universe.

3. Radiative cooling performance

3.1. Indoor setup

The schematic diagram of the indoor experimental setup is shown in Fig 2. The liquid nitrogen (77K) in a glass Dewar vessel was used as a cool source by absorbing all thermal radiation. The inner surfaces of the chamber was coated
with aluminum foil to reduce the thermal emission from surrounding objects. The samples were set above the vessel and facing down to liquid nitrogen tank. To reveal the divergence of the collected thermal emission from samples, we changed the position of samples with various distances of $h = 160$ mm, $190$ mm, and $230$ mm. The thermocouples were stuck at different places, in air close to the sample (ambient), the back surface of the sample. The different temperature of ambient air and the sample was evaluated.

3.2. Results and discussion

Fig 3 shows summarizes the RC performance at distance of 160 mm as a function of the polymer thickness, $\Delta T$. As the result of a substrate influence, $\Delta T$ of the gold film is 1.0 $^\circ$C. As for PE film, $\Delta T$ dramatically increases with the thickness and seems to be constant at 300 $\mu$m, and $\Delta T = 5.4$ $^\circ$C.

Even at thickness less than 50 $\mu$m, the fluoropolymer film ($\Delta T = 7.6$ $^\circ$C $\pm$ 0.5 $^\circ$C) expresses RC performance greater than a 300 $\mu$m-thick PE film, as high as a 350 $\mu$m-thick PDMS and soda-lime glass (1 mm thick). The soda-lime glass with silica spheres ($\phi = 20$ $\mu$m) indicates the RC performance of 7.8 $^\circ$C which is higher than that of the soda-lime glass. It corresponds to localized surface phonon polariton resonance of silica spheres at 9 $\mu$m, which coincides with ATW.

4. Conclusion

In summary, the fluoropolymer film promises for daytime RC due to its transparency in the visible regime and strong thermal emissivity in the transparent window of the Earth’s atmosphere ($8$ $\mu$m-$13$ $\mu$m). By the indoor experiment, a temperature reduction of 7.6 $^\circ$C was realized in a 50 $\mu$m-thick fluoropolymer film. Furthermore, the fluoropolymer film with good paint-ability and weather-resistant property is expected to apply in a wide range of cooling buildings and solar cells.

References

Light-matter interactions in new materials and meta-architectures
Switchable nanooptics with conducting polymer nanoantennas

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I will present our recent research on switchable nanooptical resonances in nanostructures of organic conducting polymers, and the use of such materials in display applications.

Plasmonic nanostructures have been investigated for a wide variety of applications due to their ability to control light at the nanoscale. However, plasmonic nanoantennas based on conventional metals like gold or silver are difficult to tune after fabrication due to fixed material properties. The quest for dynamically controlled optical nanoantennas has therefore stimulated an exploration of more exotic plasmonic materials, such as phase-change materials, metal oxides and polycyclic aromatic hydrocarbons. Here, I will present our research on organic conducting polymers as switchable plasmonic materials. Conducting polymers are conjugated materials that conduct electricity via polaronic charge carriers on their backbone [1]. The density of these charge carriers can be controlled via oxidation or reduction of the polymer, which dramatically affects the electrical and optical properties. Many researchers have utilized such switchable properties for reflective display applications, where our contributions include grey-scale displays [2], infrared devices [3], and hybrid systems by combination with plasmonic metasurfaces [4]. More recently, we demonstrated that nanodisks of certain conducting polymers themselves can sustain dipolar plasmonic resonances and act as optical nanoantennas in the near-infrared. Furthermore, these resonances can be repeatedly turned on and off via chemical oxidation and reduction of the polymer. [5]. These type of switchable optical nanoantennas may pave the way for a new type of organic dynamic nanooptics.

References


Adaptive Photonic Metamaterials by Self-Assembly of Liquid Crystals in Nanoporous Solids

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Abstract

Self-organized multiscale porosity in terms of precise pore size, shape, and orientation has been achieved in many base materials. Here we exemplify that in combination with self-assembly of liquid crystals in pore space this provides particularly versatile pathways for the engineering of photonic metamaterials. We present temperature-dependent structural characterizations of the thermodynamic and structural self-assembly behavior of the liquid crystals confined in nanoporous silicon, silica and alumina in combination with experiments on the resulting effective optics of the hybrid materials.

Self-assembly of radial aligned rings and axial aligned columns of disk-like molecules (HAT 6) in cylindrical alumina nanopores as evidenced by X-ray diffraction. This results in an either prolate or oblate ellipsoid of refractive indices (indicatrix) aligned to the pore axis direction. Thus, linear polarized light is split up by a parallel array of such pores into two beams with perpendicular polarizations and distinct propagation speeds. Their relative phase shift (retardation R) after passing the birefringent pore array is positive or negative, respectively, and vanishes upon heating to the isotropic liquid state.

Nanoporous media exhibit structures significantly smaller than the wavelengths of visible light and can thus act as photonic metamaterials. Embedding liquid crystals in pore space provides additional opportunities to control light-matter interactions at the single-pore, meta-atomic scale. Here, we present reciprocal space mappings employing synchrotron-based 2D X-ray and neutron diffraction in combination with high-resolution birefringence experiments on disk- and chiral rod-like molecules confined in monolithic nanoporous silicon, silica and alumina. As a function of pore hydrophilicity and thus distinct molecular anchoring at the pore walls we observe a remarkably rich self-assembly behavior, unknown from the bulk state, such as a quantized formation of concentric discotic rings [1], a transition from axial to radial aligned discotic columns [2, 3] and the formation of pore-axis aligned supermolecular helices [4, 5]. Intimately related with this surprising self-organization at the nanoscale the soft-hard hybrid materials exhibit novel metaphotonic functionalities encompassing optical anisotropy step-wise
changing with temperature [1], adjustable positive and negative birefringence [2], enhanced light rotation and extremely fast electro-optically active Goldstone excitations typical of para-to-ferroelectric phase transitions [3]. From a more general perspective our study shows, how the combination of functional soft matter with nanostructured porous solids [6] allows one to bridge the gap between bottom-up self-assembly of molecular systems with the top-down self-organisation of porosity in monolithic scaffold structures for the design of 3D mechanical robust materials, which is a particular challenge for embedding functional nanocomposites in macroscale devices.

References


Forward Prediction and Inverse Design of Plasmonic Metasurface Structural Color by Deep Learning
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Abstract
Here, optimized Deep Neural Network models are presented to enable the forward and inverse mapping between metamaterial structure and corresponding color. The forward model can predict color with >96% accuracy, with a 10⁵ order of magnitude decrease in computational time when compared to simulations. For the first time, the use of synthetic training data for self-learning is reported which results in a 15% improvement in training accuracy of the inverse model. The findings enable the discovery of new photonic materials.

1. Introduction
The inverse design of nanophotonic structures, meaning the design of an optimal meta-material given a desired spectral response, would be of great commercial value enabling the acceleration of material development and the discovery of new structures. Due to the high dimensionality and complexity of the phenomena responsible for structural color, the inverse design remains a challenge [1].

Recently, the field of scientific machine learning (SiML) has emerged, attempting to solve some of science’s most challenging problems using artificial intelligence (AI). The abundance of data, enabled by the acceleration of computational science, has allowed for highly complex relationships to be approached as data-driven statistical optimizations. SiML has generated much excitement in the photonics community and early studies report success with AI-aided design for a limited range of metamaterials [2].

In this work polydimethylsiloxane (PDMS) nanorod metasurfaces with aluminum (Al) coatings are used as a proof of concept for the development of DL models, as they provide a sustainable and commercially viable material.

Variations on this plasmonic structure have been hailed by other research groups showing desirable and robust optical properties [3]. Specifically, the use of PDMS makes these metasurfaces flexible and can allow for real-time color tuning, a promising avenue for next-generation active photonic devices [4]. In addition to the development of a practical tool for the forward and inverse design of the structure, the methods presented here provide a generalized approach to the development of DL models for structural color.

Figure 1: Schematic illustration of the metasurface used in this study. The pitch, thickness of the metal, height, and diameter of the pillars are shown with P, t, h, and d, respectively.

2. Results and Discussion
The forward deep neural network (FDNN) was trained using data collected from FDTD simulations, where structural colour is compressed to the 2D CIE 1931 chromaticity space. The optimal architecture was found to be a fully connected DNN of 7 hidden layers, each composed of 950 neurons, employing ReLU activation functions. When evaluated on the test set, the model predicted structural color with 96.03% accuracy, where accuracy is defined as the MSE between model predictions and ground truths. Figure 2 displays a qualitative representation of test accuracy, showing the model’s ability to predict colors across the gamut.

The FDNN model can be used to replace numerical simulations in the forward design process and critically provides a 10⁵ order of magnitude decrease in computational time when compared to FDTD simulations. In addition, the
FDNN model may be used as a sub-optimal inverse design tool when an external optimization method such as GA is used [5].

Unlike the forward mapping, inverse relationships between color and structure are many-to-one by nature, meaning that multiple structures may exhibit identical or near-identical EM properties [1], leading to difficulties in inverse deep neural network (IDNN) training. Here, an autoencoder architecture is used to overcome the fundamental issue of non-uniqueness. The optimum IDNN architecture was found to be 4 hidden layers, each with 950 neurons employing ReLU and sigmoid activation functions.

Figure 2: CIE 1931 scatter plot showing FDNN model predictions on the test set. The blue and red dots are the model predictions and ground truths, respectively.

Figure 3: CIE 1931 scatter plot showing IDNN model predictions on 500 randomly generated colours. The blue and red dots are the model predictions and ground truths, respectively.

Autoencoder architectures enable unsupervised self-learning. Here, the first reported use of unlabeled, synthetic training data leads to an approximate 15% increase in training accuracy. Previous works trained similar architectures using labeled simulation data. Due to the dimensionality reduction of color to the 2D CIE 1931 domain, here, arbitrarily large sets of random colors without corresponding structures can be used in training.

3. Conclusions

A DL model was developed for the forward mapping between structure and color and can replace full-wave EM simulations with a 105 order of magnitude decrease in computational burden and predictive accuracy of >96%. Moreover, the fundamental issue of non-uniqueness for the training of inverse models was overcome using an autoencoder architecture with a pre-trained forward model. The tightly restrained inverse model can be used to design metamaterials, given desired colors with an accuracy of approximately 86%. The first reported use of un-labeled self-learning with synthetic data allowed the autoencoder model to make use of large training data and improved the training accuracy by approximately 15%. In addition to the development of metamaterial-specific models, the methods presented here provide a generalized approach to the design of complex metamaterials using deep learning.

References

Ultrastrong interaction between plasmons and photons in a terahertz photonic crystal cavity

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Abstract

Realization of strong interaction between photons and the plasmons of metamaterials in a cavity is of practical interest because it has the potential for new ways of control of metamaterials used for purposes such as sensing and information processing. Here, by employing a photonic crystal cavity and a metallic metamaterial, we achieve strong light-matter interaction between plasmons and photons in the terahertz frequency range. The measured Rabi splitting indicates that the ultrastrong coupling regime is reached. We demonstrate the nonlocal collective character of the interaction. Moreover, ultrastrong coupling between Babinet-complementary metamaterials and photons is also observed.

1. Introduction

Strong light-matter interaction in a resonant cavity is at the core of cavity quantum electrodynamics (cavity QED) research. It has been intensively studied for several decades, as it both reveals and exploits fascinating quantum-optical phenomena, such as entanglement, and also provides a promising approach to quantum computing and quantum information processing [1, 2, 3]. Strong interaction between plasmons and light was first achieved with a waveguide structure [4]. Then, strong interaction between nano-rods and photons in a Fabry-Perot cavity was demonstrated in the infrared range and applied to realize ultrasensitive sensors [5]. While it appears attractive to extend this Fabry-Perot approach to strong interaction between plasmons and photons in the terahertz frequency range, this turns out to be challenging because one cannot simply scale the Fabry-Perot cavity to the terahertz frequency range due to the strong Drude absorption in the Fabry-Perot’s metallic mirrors at these frequencies. Here, by employing a dielectric one-dimensional photonic crystal (1D PC) cavity and planar metamaterials (MMs), we achieved strong interaction between the cavity photons and the plasmon modes of the MMs at terahertz frequencies.

2. Experimental results

In our experiments, we employed 1D PC cavities [3], which were composed of a central thick Si layer as a ‘defect’ layer embedded between Bragg mirrors. Each Bragg mirror consisted of two pairs of thin Si dielectric slabs separated by air spacers, as shown in the inset of Fig. 1. All Si slabs are made from commercial high-resistivity Si wafers. We investigated the interaction of cavity photons with both Swiss-cross and split-ring-resonator (SRR) MMs; for details, see Ref. [6]. In the following, we show representative results for the latter.

With the help of simulations by the transfer matrix method, the cavity was designed for a central mode at 0.86 THz. Measurements by terahertz time-domain spectroscopy (TDS) confirmed the correct implementation of the design. This cavity was then loaded with SRR MMs of different resonance frequencies. The MMs were positioned at one of the anti-nodes of the electric field of the cavity eigenmode, where the vacuum electric field has a maximum. These anti-nodes lie on the surfaces of the defect layer. Figure 1 presents measured transmittance spectra, the resonance frequency of the respective SRR MM being given next to the respective spectral curves. It is apparent that the cavity mode splits into two hybrid coupled modes. As one varies the resonance frequency of the MM tuning it through the fixed eigenfrequency of the cavity, as shown in Fig. 1, the coupled modes show a typical avoid-crossing feature. It can be simulated well with a coupled-harmonic-oscillator model (not shown, see Ref. [6]).

When the MM mode coincides with the cavity mode, the measured Rabi splitting reaches 175 GHz, which is 20% of
the cavity’s eigenfrequency, indicative for ultrastrong coupling where the rotating-wave approximation of the theoretical treatment is no longer valid. In a control experiment, no strong interaction was recorded when the MM was positioned in a nodal position of the eigenmode’s electric field (center of the defect slab), where the vacuum electric field is zero. This verifies that our observations can indeed be understood in terms of strong coupling between the electric dipole moment of the MM and the vacuum electric field of the cavity [1]. A similar strong coupling feature was observed when Swiss-cross MMs were positioned in the cavity [6].

We also noticed that the recorded Rabi splitting increases with the density of the SRRs. Experiments were performed by changing the period of the SRR unit cells while keeping the size of each SRR unchanged. As shown in Fig. 2, the Rabi splitting increases as a function of the unit cell density. The measured dependence can be nicely fitted with a square-root function, which is a clear evidence for collective interaction [6].

In our cavity, there are two electric field maxima of the vacuum electric field. They are located on the surfaces of the defect slab. Putting one layer of planar SRR MM on each surface, one obtains the Rabi splitting as shown by the stars in Fig. 2. The measured Rabi splitting can be fitted with the same square-root function as for the case of single-surface coverage. This indicates that the strong coupling is not a result of a cavity-enhanced near-field interaction of neighboring cells, but is imparted in a nonlocal way by the radiation field which can couple well-separated unit cells even from spatial separated MMs.

We also noticed a large Rabi splitting when a Babinet-complementary MM was positioned in the nodal position of the cavity eigenmode’s electric field. Here, the magnetic field has its maximum. Such observations dramatically contrast the findings for normal MMs – as described above on this page –, where strong coupling vanishes at the node positions of the cavity eigenmode’s electric field. According to Babinet’s principle [7], an electric dipole of a normal MM turns into an effective magnetic dipole of a complementary MM. In this framework, one can understand the observed strong interaction of the complementary MM as a strong coupling of effective in-plane magnetic dipoles with the magnetic field of the cavity’s eigenmode.

3. Conclusions

We report strong interaction between metamaterials and photons in a 1D photonic crystal cavity in the terahertz frequency range. The observed large Rabi splitting indicates that the ultrastrong coupling regime is reached. The interaction is nonlocal and collective. We also included Babinet-complementary metamaterials in our studies. There, the observed strong coupling can be understood as strong interaction between effective magnetic dipoles with the magnetic field of the cavity’s eigenmode.

References


Excitonic Behavior and Photo-Carriers Transport in 2D Quantum Confined Metal Organic Chalcogenides

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Abstract

Two-dimensional (2D) excitons arise from electron-hole confinement along one spatial dimension. Such excitations are often described in terms of Frenkel or Wannier models according to the degree of exciton spatial localization and the surrounding dielectric environment. In hybrid material systems, such as the 2D perovskites, the two models break down at the intermediate regime where a different physical description is needed. We significantly enrich this framework of studies by considering a tunable air-stable material platform where covalently bonded metal-chalcogenide layers are spaced by organic ligands that provide confinement barriers for charge carriers in the inorganic layer. As representative of the material class, we consider self-assembled, layered bulk silver benzeneselenolate, [AgSePh]$_\infty$. We show that in this non-polar dielectric environment, strongly anisotropic excitons dominate the optical transitions. We then investigate the charge carriers’ transport, critical aspect for most optoelectronic devices, in a [AgSePh]$_\infty$ nanocrystal (NC) film. UV photoemission spectroscopy is used to extract the valence band energy edge and suitable metal contacts were fabricated to inject charge carriers. By temperature-dependent electrical measurements the activation energy for dark charge transport was determined to be 1.10 eV. Photo-generated carriers could be extracted and the wavelength-dependent photo-response of the NC film suggest possible use of this materials as UV photodetector. We therefore built a planar photo-detector and characterized it in terms of sensitivity and frequency-dependent response. Finally, given the versatility of the [AgSePh]$_\infty$ NC film we validated its reliability as air-stable UV detector on flexible substrates.
Polar Semiconductors as Long-Wavelength Epsilon-Near-Zero Materials

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Abstract

Polar semiconductors exhibit a region of negative permittivity between the longitudinal optical (LO) and transverse optical (TO) phonons. At energies close to the LO phonon energy, the real part of the optical permittivity approaches zero and the imaginary part is also very small, the so-called epsilon-near-zero (ENZ) spectral regime. We show how the ENZ and negative permittivity regions can be leveraged for a new generation of long-wavelength optical devices and materials.

1. Introduction

In the long-wavelength infrared (λ = 10 – 60 µm), the optical permittivity of a polar dielectric is determined primarily by light-matter interactions between optical fields and free-carriers in the crystal lattice and vibrations of the crystal lattice itself, called phonons. The interaction of light with free-carriers can be controlled via the carrier density, minimizing the effect of so-called plamons on the optical permittivity. Coupling to optical phonons however cannot be similarly controlled or minimized as the phonon energy and the optical dipole of the phonon modes are properties of the crystal lattice itself. [1]

Optical phonons typically occur at photon energies in the mid- and far-infrared. The TO and LO phonons bookend a region of negative permittivity called the Reststrahlen band. Thus, the optical permittivity in the Reststrahlen band of polar dielectric crystals is similar to metals in the visible spectrum, but polar crystals exhibit lower loss than a metal or doped semiconductor when normalized for the optical frequency of the photon. Importantly, near the LO phonon, the real and imaginary parts of the permittivity are very small; at the LO phonon energy, the real part of the permittivity is zero. This low-loss ENZ regime in polar dielectrics and semiconductors can be used to demonstrate novel long-wavelength photonic devices and materials. Here, we demonstrate how polar semiconductors can be used to (1) engineer multi-mode optical antennas with near-monochromatic optical response and (2) localized modes on extreme sub-diffraction nanoparticles.

Antennas are widely used as a coupling element to transfer between electromagnetic radiation and electrons in circuits and devices. Optical antennas have gained attention in photonics because of their ability to transfer energy between free-space modes and modes in optoelectronic devices, the bar antenna being the simplest example. The resonant mode for bar antennas occurs when the length of the bar is and integer multiple of half of the wavelength. The resonant modes can be tuned by changing the length of the antenna or the effective index of the medium. Tuning the effective index of the mode can be achieved by engineering the surround dielectric environment, and a dielectric environment incorporating an ENZ material can enable unique modal dispersion for optical antennas.

We experimentally demonstrate the coupling between the antenna modes and the ENZ modes from AlN subwavelength film. Upon increasing the antenna length, we observe that the antenna modes spectra pinning in to the near-zero index medium, giving rise to multimode response over a small wavelength range. [2] The fabricated devices are experimentally measured using angle and polarization dependent Fourier transform infrared (FTIR) reflection spectroscopy. Further, the structures are analytically modelled using rigorous coupled wave analysis (RCWA) and finite element methods and are supported by an oscillator model that provide deep insight in to coupling between ENZ mode to the antenna mode. The results are promising for designing future generation optoelectronics devices.

In addition to near-monochromatic multimode antennas enabled by the ENZ spectral region, we demonstrate how the negative permittivity region, also relatively low-loss, supports localized modes on extreme sub-diffraction ZnO nanoparticles. We measure coupling to two localized surface phonon-polaritons modes that arise due to crystalline anisotropy; we show excellent agreement between the measured energy of these modes and our numerical predictions. Furthermore, we demonstrate anomalous absorption at energies close to an optical phonon that should not couple infrared light. We provide evidence of this coupling and suspect that activation of this mode is due to symmetry-breaking in the ZnO crystal lattice.
2. Results and Discussions

The resonant modes of the bar antenna are estimated considering the geometric parameter of the antenna and it’s dielectric surrounding. Figure 1a shows the calculated reflection versus frequency and antenna length for first four modes for antennas on semi-infinite substrate with $\varepsilon=2.5$. The deep in reflectance is due to the coupling to the localized antenna mode. Interestingly, the antenna mode diverge significantly when the antenna are placed near an ENZ substrate (Figure 1b). With increasing the antenna length the modes are pinning more to the narrow frequency regime. This anomalous behaviour is due to near-zero effective index of bottom layer AlN film. The dispersion can further be altered via coupling between antenna mode with Berreman mode supported by thin film of AlN (Figure 1c).

![Figure 1](image)

Figure 1: Calculated reflectance varies as a function of antenna length and wavenumber for antennas on a) a semi-infinite substrate with $\varepsilon=2.5$, b) semi-infinite AlN, c) 1.2 $\mu$m thick AlN on Mo, d) calculated index of refraction versus wavenumber using single oscillator lorezian model (blue = AlN substrate, red = optical mode excited on an antenna) e) scanning electron microscope (SEM) image of antenna of dimension 10.71 $\mu$m$\times$145 nm f) experimentally measured TM reflection for light incident at 35° (reproduced from Dominguez et. al.[2]).

ZnO NPs with an average size of ~100 nm were prepared by solvothermal synthesis adapted from previously published work. For transmission measurements, pellets were prepared by mixing ZnO:KBr in 1:300 concentration by mass and pressed at 525 MPa using a hydraulic press. Infrared transmission measurements were performed with a Bruker Vertex 80v Fourier transform infrared spectrometer and a room temperature DTGS detector. The transmission spectrum is calculated as the ratio of the sample spectrum to the spectrum of a blank KBr pellet.

![Figure 2](image)

Figure 2: Measured extinction spectrum for ZnO NPs using an FTIR spectrometer. The measured data is fit using Voigt functions.

To identify the spectral positions of the various modes, we perform a multi-peak fit to the measured FTIR spectra using Voigt functions, which takes both Gaussian and Lorentzian linewidth shape in to account. In the IR absorption data we observe peaks/shoulders at 411 ± 0.45, 445 ± 0.28, 508 ± 0.15, and 535 ± 0.63 cm$^{-1}$ as shown in Fig. 2. The 508 and 535 cm$^{-1}$ peaks agree well with surface phonon polariton modes that are predicted by Mie scattering theory for anisotropic polar NPs. The 411 cm$^{-1}$ peak corresponds to the TO phonon frequency. There is an additional peak at 445 cm$^{-1}$ which has not been observed previously for ZnO. The 445 cm$^{-1}$ peak in the IR data is at the same frequency as the $E^{\text{high}}_2$ phonon mode which we also measure using Raman spectroscopy. The $E^{\text{high}}_2$ phonon mode is predicted to be infrared-silent for crystals. However, we believe that symmetry-disruption due to the small size of the NPs, small crystallite size, or defects can activate the mode, resulting in the strong absorption observed in our measurements.

3. Conclusions

We have theoretically modelled, numerically calculated and experimentally demonstrated the coupling between multimode antenna modes with ENZ mode supported by thin layer of AlN. The spectral pinning of these modes in a small window of frequency opens plethora of opportunities in engineering new generation optical devices and give a new direction of light-matter interactions.

References

Conformable metasurfaces for linear and nonlinear applications

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Abstract

Conformable metasurfaces retain all the properties of their rigid counterparts, while presenting unique opportunities both in terms of optical properties and applications. Here we discuss our most recent results in imaging, antenna design and nonlinear optics based on them.

1. Introduction

Flexible metasurfaces merge the versatility of rigid metasurfaces with the practical advantages offered by a supple and conformable physical platform. In particular, they can be transferred onto virtually every target material or object, they can be mechanically tuned (statically or dynamically) after fabrication and, most importantly, they can exploit the mature manufacturing technology typical of printed electronics. For some applications, the deformation of the substrate could be detrimental, hence it is desirable to realize optical functions that are robust to different types of alteration of metasurface topology (see, e.g. [1, 2]). In some other cases, as discussed below, it is instead convenient to make the optical behavior of the metasurface strongly dependent from the very specific shape of its topology [3].

2. Discussions

The typical fabrication procedure of conformable metasurfaces replicate the standard nanolithography approaches developed for metallic or dielectric based metasurfaces. The main difference is the adoption of a release layer, typically inserted between a sacrificial rigid carrier and a polymeric layer, which acts as the conformable substrate of the metasurface. Different applications may require tailored conformability properties, hence it is important to control the locality of the mechanical response to variation of the shape of the substrate, when the metasurface is conformed to a given target. The key factors to consider are the thickness of the support and its young modulus. Another key consideration when choosing the most suitable substrate is the compatibility of the polymeric layer with the overall fabrication process (e.g. the chemical orthogonality between subsequent steps).

In this communication we first discuss the fabrication procedures to realize different type of flexible metasurfaces and then discuss in details applications in holographic imaging from the visible to the mm-wave range, for biophotonics and radar applications. Specifically, we demonstrate that it is possible to define conformable holographic patches that are tailored to the target substrate that they are applied to. In the visible range, this capability is perfectly suitable for anticounterfeiting applications, whereas at mm-waves they can be used for antennas and signature control applications [3, 4].

Finally, we discuss the development of epsilon near zero metasurfaces, demonstrating that we can fabricate free standing, conformable flexible ENZ membranes. Our approach permits to coat any material or device with a tailored made photonic skin, decoupling the fabrication requirements from the complexity of the shape of the object to be coated. For this class of conformable metasurfaces, we demonstrate that the obtained membranes do not show any sign of degradation even after several thousand bending cycles and that our ENZ material can conform on targets with radius of curvature of a few microns, as shown in fig. 1 [5].

3. Conclusions

Flexible and conformable metasurfaces are a versatile platform which will enable the adoption of the metamaterial technology in real life applications.

Acknowledgement

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3.1. References

References

Figure 1: Figure 1. a) Retrieved real part of the effective permittivity of the ENZ material (inset) vs wavelength, for different bending cycles (BC). b) SEM view of a ENZ membrane conformed on a polystyrene bead. c) SEM image of the cross section of panel b). d) SEM image of the cross section of the ENZ skin.

Exciton Resonance Tuning in Atomically-Thin Optical Elements

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Abstract

Next-generation flat optics require dynamic control over optical functionalities. We demonstrate accurate control over light scattering by exciton resonances in monolayer WS2 by controlling the dielectric environment of the monolayer. Next, we demonstrate actively-tunable and atomically-thin optical lenses by carving them directly out of monolayer WS2. Using ion-liquid gating to dynamically manipulate the material’s exciton resonance we show active modulation of the focal intensity.

1. Introduction

Since the development of diffractive optical elements in the 1970s research has focused on replacing bulky optical elements such as lenses and gratings by thin counterparts. Over the last decade, nanophotonic metasurfaces rapidly advanced the development of flat optical elements based on the realization that resonant optical antenna elements enable local phase control. Present applications of metasurface flat optical elements include lenses, polarization control, and beam steering. Next-generation applications of flat optics require dynamic control over optical functionalities, e.g. the focal position or efficiency of optical elements. However, most nanophotonic structures are static after design and fabrication. Current approaches for dynamic control like electrical gating exhibit limited tunability due to the finite few-nm extend of the depletion and accumulation layers as result of Coulombic screening.

Here, we demonstrate accurate and active control over light scattering by monolayer transition-metal dichalcogenides (TMDCs) like WS2 with a strong excitonic resonance in the visible spectral range, and use this to realize actively-tunable and atomically-thin optical lenses. First, by engineering the dielectric environment around the monolayer, we manipulate the complex interference of light scattered by the monolayer and the underlying substrate. As a result, we gain accurate control over the line shape of the exciton resonance in the reflection spectrum. Next, we realize actively-tunable and atomically-thin optical lenses by carving them directly out of monolayer WS2. This turns the 2D material into the antenna or metamaterial and incorporation of active materials into larger antenna structures will no longer be needed. Due to their sub-nm thickness, these materials are highly tunable through external control. We demonstrate dynamic electrical tuning of the focusing efficiency through manipulation of the excitonic material resonance properties as opposed to tuning of antenna resonances.

2. Controlling exciton resonance line shape through the dielectric environment

Large-area monolayer WS2 on a fused silica substrate is obtained commercially, and the optical constants are measured using spectroscopic ellipsometry. To create an in-situ reference, half of the monolayer surface area is removed by a combination of physical masking and reactive-ion etching to expose the bare substrate. Next, we drop cast oils with varying refractive index on top of the monolayer WS2 and cover the oil with a glass cover slip. By varying the oil refractive index, we accurately control the substrate reflection amplitude and phase and thereby the interference with the light scattered by the monolayer’s exciton resonance. Using local reflection measurements, we characterize the line shape of the exciton resonance in the reflection spectrum, and show accurate control over the spectral asymmetry. Using transfer-matrix calculations based on the measured optical constants to match the experimental results, we highlight the important role of the substrate contribution to the spectral line shape as a result of complex interference with the light scattered by the exciton resonance.
Figure 1: Accurate control of exciton resonance line shape in the reflection spectrum by tuning the dielectric environment (oil refractive index).

3. **Focal intensity modulation of an atomically-thin lens**

To realize atomically-thin dynamic metasurface optical elements, large-area monolayer WS\(_2\) on sapphire is obtained commercially and covered by a monolayer of graphene (Gr) through large-area manual wet-transfer. The graphene functions as a transparent conducting electrode to provide homogeneous gating of the WS\(_2\). Next, Au electrodes and reference pads are fabricated using optical lithography, metal deposition and lift-off. The Gr/WS\(_2\) bi-layer is then patterned into Fresnel zone plates through e-beam lithography and reactive-ion etching. The lens has a 1 mm diameter with a focal length \(f = 2\) mm. Finally, an electrochemical cell is fabricated on top of the sample and filled with ionic liquid (DEME-TFSI) to facilitate gating of the WS\(_2\).

Figure 2: Atomically-thin zone plate carved into a 2D material with a strong excitonic response. Active tuning of the focusing intensity is demonstrated and quantified.

Using confocal microscopy, we characterize the focus that is formed above the surface in transmission (illuminated through substrate), and demonstrate active modulation of the focal intensity.

4. **Summary**

We demonstrate accurate and dynamic control over light scattering by monolayer WS\(_2\) on substrates. First, we tune the dielectric environment of a monolayer to control the exciton resonance line shape in the reflection spectrum. Next, we realize actively-tunable and atomically-thin optical lenses by carving them directly out of WS\(_2\). Using confocal microscopy, we characterize the focusing efficiency spectrum and identify the role of excitonic light scattering in the efficiency spectrum. Next, we employ ion-liquid gating to actively manipulate the excitonic materials resonance and use this to demonstrate active intensity modulation in the focus of the lens.
Enhanced light coupling into nanostructured arrays as an enabler for advanced Raman-based metrology

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Abstract

The continuous scaling of devices, cells and functions in semiconductor processing industry to boost the performance per area and cost has led to device architectures below 10 nm becoming a high-volume manufacturing reality, while pathfinding for future technology nodes increasingly emphasizes the further exploit of high-aspect ratio structures [1]. Most of the integration schemes for such architectures share a phase where ultra-narrow lines are patterned in a grating-like fashion with alternating materials with different optical properties. As the dimensions of these structures shrink, the need for precise control and metrology of the pitch and critical dimension (CD) throughout the different processing steps becomes of paramount importance. Recently it was found that when coherent polarized light impinges on such nanogratings, these arrays act as photonic crystals with very particular allowed and forbidden light propagation modes [2–3]. As it turns out, the coupling of light into the structure is exceptionally sensitive to the parameters that define the periodicity, i.e. the pitch and CD. As Raman scattering scales with the fourth power of the local electric field, this effect re-opens the possibility for Raman spectroscopy to excel as a non-contact probe for phase, stress but also CD of nanostructured devices far beyond the diffraction limit. Indeed the profound understanding of this enhanced light coupling has opened a plethora of metrology applications based on the analysis of the Raman scattering originating from these nanogratings. We will show how as such Raman spectroscopy is able to probe mechanical stress, composition, critical dimension, etc. at the nanoscale.

References


Ultra-Compact Photonic Modulator based on Accumulation-Layer Surface Plasmons

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Abstract

Most commonly studied electro-optic modulators employ several electro-optical mechanisms such as Pockels, Kerr, or carrier concentration change effects to modulate the phase and amplitude of light propagating through the device. In this work, we consider a transparent conducting oxide (TCO) based electro-optic modulator and demonstrate the propagation of surface plasmons due to the accumulation of carriers in the thin TCO layers under external electrical bias.

1. Introduction

Electro-optic modulators constitute a large portion of the research in photonics engineering and data communication technology owing to the ever-rising demand of large bandwidth requirements. Dominant materials used in commercial modulators and researched extensively on are lithium niobate and silicon. Transparent conducting oxides (TCOs) are an upcoming material platform that can induce carrier concentration effect in the primary modulator structure. Highly doped wide-bandgap TCOs can be driven into the so-called epsilon-near-zero region by tuning the carrier concentration while simultaneously operating in the telecommunication wavelength. In this work, we analyze several multilayer structures that include a thin TCO layer to be utilized in ultra-compact, CMOS-compatible plasmonic modulators (Fig. 1). Changes in the refractive index of TCO arises from the accumulation and depletion of carriers, aiding the modulation of light in the process. In addition, we numerically study the transmission properties of the modulator under variation of the length of the TCO-containing modulator segment, and we show that the signal can be efficiently modulated in the devices of about micrometer in length.

2. Model

Different plasmonic materials including TCOs are studied as constituent building blocks of the investigated geometries [1]. Furthermore, transparent conducting oxides may serve as a dynamically-switching element [2], and the efficient modulation is achieved by tuning the carrier concentration in the TCO layer into and out of the plasmon resonance with an applied electric field.

Figure 1: (a) General scheme of a compact modulator integrated with low-loss plasmonic waveguides. In this geometry, a stripe waveguide is used to bring a long-ranging plasmonic mode to and from the modulator structure where an applied voltage modulates the SPP wave. (b) Mode profiles in waveguide and modulator parts.

The large modulation depth is enabled by the resonance of the absorption coefficient of the structure. Moreover, the usage of other plasmonic materials in modulator configurations allows achieving significantly increased modulation depth [3].

3. Discussion

Various modulator layouts are investigated and the typical trade-off between compactness and propagation loss is analyzed in detail. We define a figure of merit and discuss results for modulator performance and mode size as
functions of the carrier concentration in the TCO layer (fig. 2). We show that an extinction ratio of 20 dB/µm can be achieved, allowing for a 3-dB modulation depth on a scale of hundreds of nanometers at telecommunication wavelength. We investigate the integration of the most efficient modulator with plasmonic waveguides and analyze its performance in terms of coupling losses and integration possibilities. The ability to easily integrate with existing semiconductor systems could enable new devices for applications in on-chip optics, sensing, optoelectronics, data storage, and information processing.

Figure 2: (a) Absorption coefficients $\alpha$ for various carrier concentrations of TCO. (b) Field distributions in the guiding parts of the device.

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References
Unlocking the far-IR potential in plasmonics with metal oxide perovskites

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Abstract

In order to fulfill the promise of plasmonics, it has been viewed that one of the most disruptive technologies will be the “all dielectric plasmonics” [1]. This, by itself, contradicts the definition of plasmonics (interaction of light with collective charge oscillations at metallic nanostructures). However, some interesting approaches can be exploited. In that respect, polar dielectrics can be used to couple an electromagnetic field to collective lattice oscillations, namely optical phonons. Those polar crystals can support optical modes that are confined either to the surface of the material or can be highly confined within or in the vicinity of sub-wavelength geometries, resulting in strong field enhancement. Similar to their metallic counterparts these oscillations are only supported when the real permittivity is negative and in the case of the polar dielectrics, this happens at the so-called Reststrahlen band. Naturally, the extent of this band is of great interest since it defines the spectral range of operation [2].

Here, we focus our attention to a family of very important technological materials; that of metal oxide perovskites. Metal oxide perovskites have been investigated for many years due to their excellent dielectric, piezoelectric, ferroelectric and optoelectronic properties [3,4]. When a small number of electrons are introduced in the lattice (e.g. in oxygen-deficient samples or doped with metals, such as Fe [5] or Nb [6]) many other attractive properties arise such as superfund conductivity, ferromagnetism, high thermoelectric coefficient, blue and green light emission as well as accommodation of a two-dimensional electron gas. We present their exceptional capabilities, in terms of their bulk and surface properties and medium properties and photonic crystal superstructures of metallic nanoparticle arrays. J. Appl. Phys. 101, 54304 (2007).

References

Watching operating Li-ion batteries by Raman through hollow-core optical fibres

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Abstract

We demonstrate a new fibre-optic sensing method capable of monitoring chemical changes within Li-ion cells under real working conditions. Our experiments are based on optofluidic hollow-core fibres, that allow light to be guided over long path lengths at the centre of a microfluidic channel. We have previously shown that such microreactors can be used to probe a range of different photochemical and catalytic processes by sensitive in-operando absorption spectroscopy [1]. Here, we integrate hollow-core fibres into working Li-ion cells with minimal perturbation on their operational and structural integrity [2-4]. The hollow-core fibres are used to take sub-microlitre samples of the electrolyte liquid that are analysed by background-free Raman spectroscopy [5,6] to identify early signs of battery degradation in-operando.

This sensing strategy uniquely enables us to monitor important battery state-of-health indicators [7], such as the depletion of additives and the formation of a functional solid electrolyte interphase: a buffer layer that is essential for a stable battery operation. The method complements existing electrochemistry approaches to battery science, and can be used as a powerful diagnostic tool for stationary energy storage plants and electric-vehicle battery packs.

References

Photo-magnetic recording with L-band ultrashort laser pulses in dielectric medium

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Abstract
We experimentally demonstrated the possibility of the potential use of ultrashort laser pulses at telecommunication L-band to all-optical magnetic recording. A single linearly polarized laser pulse near 1590 nm wavelength switch the magnetization between two states in Co-doped YIG thin transparent film. Changing the linear polarization of the laser pulse, we can write-erase magnetic area in the sample.

1. Introduction
The recent discovery of ultrafast magnetization switching in cobalt-doped yttrium iron garnet (YIG:Co) has again increased interest in this material [1-3]. Low energy consumption, short time of operation and a small amount of cumulated heat make it potentially useful in processing and transfer of data. Since the whole process is based solely on the interaction of light with matter, it could be possible to find an application of magnetization reversal in combination with fiber communication resulting in even faster digital data transfer. Recently have been demonstrated all-optical switching for ultrashort laser pulses with wavelengths of 1140 nm and 1300 nm (O-band) [1, 2]. Here we found the more efficient wavelength range near 1550-1600 nm, which would be excellent for the demands of modern communication systems at the near-infrared spectral range.

2. Experiment and results
The sample used in the experiment was a 7.5 μm thin optically transparent YIG:Co film [1]. To investigate the magnetization switching induced by femtosecond linearly polarized laser pulses in YIG:Co thin film, we employed the technique of magneto-optical polarized microscopy in Faraday geometry. The duration of a single pulse was about 50 fs, and the wavelength of the pump pulse was tuned within the range between 1550 nm and 1600 nm. Comparison of images taken before and after the shot gave information about changes in the magnetization. Garnet was restored to the original state with the brief, strong magnetic field or with another light pulse, but with polarization orthogonal to the previous one.

The research confirmed a strong response in the wavelength range of O-band and revealed the existence of electron transition in Co-ions near the wavelength of 1590 nm [4]. Detailed measurements with changing pump beam polarization for L-band show that the most efficient photo-magnetic switching is observed for two directions (along crystallographic axes [100] and [010]), which is consistent with previous results for O-band [2].

Figure 1 shows the spectral selectivity photo-magnetic switching with L-band and O-band. The absorption spectra of YIG:Co in the range of photon energies from 0.5 eV to 2 eV show several additional peaks associated with Co-ions. The most pronounced peaks are observed around the wavelength 1100 nm, 1300 nm and 1580 nm. The first peak in the Fig. 1 is the least efficient, and due to that, it needs around 5 pulses. For switching with pumping around 1300 nm and 1590 nm, only a single laser pulse was used. The threshold fluence for the single pump at 1300 nm was below 40 mJ/cm², while for 1590 nm the threshold is about 72 mJ/cm². However, in case of YIG:Co film, the absorption was around 11,2% for 1300 nm and 4,4% for 1590 nm [5], which results in the intake of 4,5 mJ/cm² and 3,1 mL/cm² respectively.
Such a result proves that magnetization switching for L-band is not only more convenient than for O-band, but also more energy-efficient.

3. Conclusions

We have demonstrated that magnetization reversal for L-band is possible with the highest efficiency using a single pump laser pulse at 1590 nm. Small energy consumption and high writing speed may be useful in modern data processing, especially in connection with fiber communication technology.

Acknowledgements

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Designing with spins: magnonic metamaterials based on nanoengineered spin textures

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Abstract
Magnonics seeks to control the excitation, propagation and transduction of spin waves, i.e. propagating perturbations in the arrangement of spins in magnetic materials, for information processing. Here, we present our recent work on the manipulation of spin waves in nanoengineered magnetic materials. First, we present a technique, tam-SPL, for nanopatterning spin textures in magnetic multilayers. Then, we discuss the use of spin textures for controlling the emission, propagation and interference of spin waves, aiming to develop energy-efficient wave-based computing platforms. Nevertheless, controlling spin waves at the nanoscale, which is crucial for the realization of magnonic nanodevices, is extremely challenging, due to the difficulty in controlling the nanoscopic magnetic properties with conventional nanofabrication techniques. Recently, we developed a new technique, called thermally-assisted magnetic scanning probe lithography (tam-SPL), which employs a heated nanometric scanning probe for tailoring the magnetic properties of thin film heterostructures, and stabilize complex spin textures such as two-dimensional magnetic domains, one-dimensional domain walls and zero-dimensional topological solitons with highly controlled properties.

1. Introduction
The main powerful enabling features of spin waves are the absence of Joule losses associated with spin-wave propagation, the short wavelength in the GHz-THz range, which can go down to a few nm, and the extremely rich phenomenology, which makes magnonic very promising for implementing highly-integrated and energy-efficient wave-based computing platforms. Nevertheless, controlling spin waves at the nanoscale, which is crucial for the realization of magnonic nanodevices, is extremely challenging, due to the difficulty in controlling the nanoscopic magnetic properties with conventional nanofabrication techniques. Recently, we developed a new technique, called thermally-assisted magnetic scanning probe lithography (tam-SPL), which employs a heated nanometric scanning probe for tailoring the magnetic properties of thin film heterostructures, and stabilize complex spin textures such as two-dimensional magnetic domains, one-dimensional domain walls and zero-dimensional topological solitons with highly controlled properties.

Here, we present the working principle and capabilities of tam-SPL, and discuss our recent results on the realization of magnonic metamaterials, where 2D-1D and 0D engineered spin textures are used for controlling the emission, propagation and spatial confinement of spin waves.

Figure 1: a. Sketch of the tam-SPL patterning, performed by sweeping a heated scanning probe on the sample in presence of an external magnetic field \( H_{\text{ex}} \), for locally resetting the exchange bias. b. Magnetic Force Microscopy image of arbitrary shaped magnetic domains. Black arrows indicate the direction of the magnetization in the patterned and non-patterned regions. Scale bar: 2 \( \mu \)m. c. Micromagnetic simulations showing the spin configuration of the domain walls.
2. Thermally assisted magnetic scanning probe lithography (tam-SPL)

Tam-SPL[1] is carried out by sweeping the heated probe on the surface of an exchange bias magnetic system in presence of an external field, for performing a highly localized field cooling and locally re-setting the magnetic anisotropy point-by-point with nanoscale resolution. In turn, this allows one to deterministically stabilize complex magnetization configurations. Figure 1a shows the working principle of the technique in the simplest case of an exchange bias ferromagnet/antiferromagnet bilayer magnetized in plane. As the tip is displaced across the sample, the previously heated region undergoes a highly localized field cooling, and the local magnetic anisotropy is re-set in the direction of $H_w$. By controlling the patterning conditions and the geometry of the patterned area, it is possible to deterministically stabilize a wide range of spin textures with tailored properties and dimensionality. In particular, magnetic domains with arbitrary shape and spin-configuration (see Figure 2b), domain walls, i.e. regions at the domain boundaries where the magnetization rotates from one direction to the other (see Figure 2c), and magnetic solitons such as vortices and Bloch lines with deterministically tailored topolgy and position [2]. Another appealing feature of tam-SPL is its full reversibility, leading to fully reconfigurable magnetic metamaterials. In fact, writing, erasing and rewriting patterns can be done simply by sweeping the heated tip on the same region while applying a different writing field $H_w$.

3. Nanomagnonics with engineered spin-textures

Here, we show that such engineered spin-textures can be used effectively for controlling the emission, propagation and confinement of spin waves. In particular, we show that the spin-wave excitation and propagation can be spatially controlled with nanoscale resolution, and that the spin-wave properties of the magnonic material can be modulated reversibly via external fields.

Figure 2: a. Domain wall based magnonic nanoantennas. a. Simulations of the emission of a focused directional spin-wave beam by a domain wall. b. Corresponding time-resolved experimental image of the spin-wave beam emitted be the curved wall (red line), propagating in a synthetic antiferromagnet. Scale bar 500 nm.

Then, we demonstrate the channeling and steering of propagating spin-waves in arbitrarily shaped nanomagnonic waveguides based on straight and curved domain walls, and a prototypic nanomagnonic circuit comprising two converging waveguides, allowing for the tunable spatial superposition and interference of confined spin-waves modes [3]. Finally, we present an optically inspired platform for controlling the generation, propagation, and interference of short-wavelength spin waves, using nanopatterned spin textures in synthetic antiferromagnets [4]. We demonstrate the spatial engineering of spin-wave wavefronts via tailored magnonic nanoantennas, the directional emission and focusing of spin-wave beams, and the controlled generation of robust interference patterns which span multiple times the spin-wave wavelength. Furthermore, we show that SAF materials allow combining concepts borrowed from optics, with phenomena naturally arising from the nonreciprocal spin wave dispersion, such as resilience to spurious back reflections.

4. Conclusion

The ability to control magnons via nanoscale-designed magnetic metamaterials based on spin-textures opens up a plethora of new possibilities for the realization of energy-efficient digital and analog computing platforms. Future applications include reconfigurable microwave filters, isolators, and devices for pattern and speech recognition based on the emission, manipulation, and interference of coherent spin-wave wavefronts at the nanoscale.

Acknowledgements

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References


Single-shot time-resolved imaging of all-optical ultrafast magneto-optical switching

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Abstract
The understanding of fundamental mechanism allowing for all-optical magnetization switching in femtosecond time scale is a key for providing novel outperforming applications. Recently, it has been discovered that only by a single laser pulse, extremely fast (about 20 ps), reversible and repeatable photo-magnetic switching in Co-doped yttrium iron garnet films can be obtained. Here, we demonstrate the experimental technique enabling visualization of magnetization switching at femtosecond time scale using single-shot time-resolved magneto-optical imaging in YIG:Co films.

1. Introduction
The interest in the manipulation of the magnetic order by subpicosecond laser pulse has been growing for over two decades [1, 2]. Researching new types of materials push the achievable boundaries towards new records of the switching speeds and minimal heat loads. However, it requires developing new theoretical mechanism allowing for an underlying understanding of ongoing processes [3]. It has been already shown that single laser pulse without any external magnetic field can switch magnetization in Co-doped yttrium iron garnet films. Such switching happens in an extremely short time about 20 ps with the unprecedentedly low heat load.

For the detailed temporal and spatial investigation of magnetization dynamics, we employed the time-resolved single-shot magneto-optical imaging at Faraday geometry. We tried to retrieve and separate the magnetic signal from the optical absorption and demonstrate the spatial dynamics of the ultrafast photo-magnetic switching in YIG:Co films.

2. Setup Design
The setup used for the investigation of the magnetization dynamics duplicates the conventional pump and probe experiment expanding its possibilities. We used laser pulses from a Ti:Sapphire laser system with an amplifier at a 1 kHz repetition rate. Two independently tunable optical parametric amplifiers were used to generate pump and probe pulses. The mechanical delay line introduced into the probe beam path gives the possibility of adjusting the optical path difference between two beams. Thus, setting it to the desired distance defines with the femtosecond precision the time delay between probe and pump pulse.

To observe magnetic contrast in the captured image, the principle of the polarizing magneto-optical microscope, was applied. The light propagating through the sample is affected by the magneto-optical Faraday effect. It induces rotation of the plane of polarization proportional to the amount of the magnetization component projected on the direction of the light propagation. In used Faraday polarizing microscope geometry, linearly polarized probe pulse propagates through the sample and after it, it is collected by the objective. Afterwards, the pulse passes through the analyser. The mutual rotation between polariser and analyser defines magneto-optical contrast.

The magnetization in YIG:Co thin films was switched by the linearly polarized single pump pulse at 1300 nm wavelength and 50 fs pulse duration. Imaging was performed by illuminating the sample with an unfocused 650 nm probe beam. To erase a long-living state with the switched magnetization and to initialize the magnetic state, a magnetic field was applied after each single-shot event. Repeating such a single pump and single probe measurement for multiple values of the delays between the pump and the probe pulses, we acquired images of the magnetic domains at various time moments after the arrival of the pump pulse. Every image is registered on the synchronized and triggered by the probe pulse CCD camera.

3. Time-resolved imaging
To determine the influence of pump pulse on magnetic structures, one has to separate the contribution of magneto-optical Faraday effect from the effects contributed by optics. Here, the visible difference comes from the rotation of the polarization plane of the probe beam, which passed through the sample. Therefore, the setup is sensitive to the probe beam polarization rotation.

While propagating through the sample, the probe beam interacts with the magnetic field given by the sample’s domain structure. Different orientation of the magnetization component of magnetic domains results in the different Faraday rotation of the polarization plane, which is detected on the camera.

The series of the magneto-optical images were obtained by changing the time delay (see Fig. 1). To quantify the dynamics of the laser-induced changes, we took an integral
over the pumped area, normalized the data and plotted the result as a function of a time-delay between the pump and probe pulses. Therefore, creating a repeatable series of images is an easy way to retrieve the information concerning time and localization of pump induced changes. Obtained exemplar image stack (Fig. 2) contains information about the relative time delay between images, which is retrieved from the mechanical stage step distance.

Figure 1: Single-shot time-resolved magneto-optical images for the different time delay between the single pump at 1300 nm and probe at 650 nm pulses. The last image shows switched magnetic domains.

Figure 2: Time-dependence of the normalized out-of-plane magnetization component with different pump fluence $I$. The data points were calculated as the ratio of the magneto-optical signal (the average image contrast) in the switched area to the magneto-optical signal in the case when the magnetization is aligned along the [001] axis. The solid lines were fitted using the exponential functions with the characteristic time $\tau$. 

4. Conclusions

The used experimental technique allowed for detailed simultaneous examination of the temporal and spatial magnetization dynamic properties in the investigated sample. The magnetic contribution from magnetic effects can be qualitatively distinguished from other optical effects.

Acknowledgements

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References

Frequency tripling via sum-frequency generation by single AlGaAs nanocylinders

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Abstract

Dielectric nano-antennas of III–V semiconductor materials offer a strong nonlinear response governed by the electromagnetic resonances of the system. We investigate individual AlGaAs cylinders and observe efficient sum-frequency generation by mixing an input beam of telecom frequency with its second harmonic. Our work highlights a convenient frequency-tripling pathway at the nanoscale based on the second-order nonlinearity of the material.

1. Introduction

Nonlinear optical processes have low efficiencies in subwavelength systems since the amount of material involved is small and a coherent build-up of the emission over multiple wavelengths (“phase matching”) cannot occur. High-refractive index dielectric nanostructures recently gained attention for their ability to enhance the nonlinear conversion, thanks to the strong light confinement they exhibit at their resonant modes. The sensitive dependence of the resonant modes on the geometry and material composition offers ample opportunities to tailor the optical properties of the system and cater the needs of different applications. In particular, our collaboration studied extensively a monolithic AlGaAs antenna platform, see Ref. \cite{1,2}, and reported intense second-harmonic generation (SHG), owing to the large second-order susceptibility and non-centrosymmetric (zincblende) crystal structure of III–V semiconductors. We then moved on to other second-order processes such as spontaneous parametric down conversion of Ref. \cite{3} and the sum-frequency generation (SFG) scheme presented here.

2. Experiment

In this work we investigate individual Al\textsubscript{0.18}Ga\textsubscript{0.82}As antennas fabricated with electron-beam lithography as described in Ref. \cite{1}. The antennas are cylinders of 400 nm height oriented along the [001] crystal direction, and radius \(R\) ranging between 165 nm and 365 nm in steps of 6 nm. They are milled on a low-refractive index AlO\textsubscript{x} (\(n = 1.6\)) substrate, in order to achieve a strong optical confinement within the AlGaAs volume (\(n = 3.2\)).

The laser source we use provides pulses (160 fs duration, 80 MHz repetition rate) centered at an angular frequency \(\omega\) corresponding to the wavelength \(\lambda = 1554\) nm. The pulse train is partially duplicated in frequency to \(2\omega\) before the sample. As illustrated by the inset of Fig. 1, the experiment consists in mixing the two frequencies via the second-order susceptibility \(\chi^{(2)}\) of the antenna to detect SFG at \(\omega + 2\omega = 3\omega\). This process is coherent and degenerate in the output frequency with third-harmonic generation (THG), which is mediated by the third-order susceptibility \(\chi^{(3)}\) instead.

3. Results and discussion

We varied the delay between \(\omega\) and \(2\omega\) pulses to record traces such as the one in Fig. 1. As we are detecting photons at \(3\omega\), some THG produced by the excitation at \(\omega\) is always measured. The \(2\omega\) beam alone yields instead no detectable signal, but when temporally (as well as spatially on the sample) superimposed to the \(\omega\) beam an additional SFG emission is observed on top of the THG plateau. The narrow and symmetric correlation peak indicates that the interaction between pulses is electronic rather than thermal in character. Single-particle spectroscopy (not presented here) rules out broadband luminescence contributions such as two-photon fluorescence excited at \(2\omega\). The THG and SFG nature of the observed signals is confirmed by their
dependence on the pump powers (not presented here). Interference between THG and SFG gives rise to a fringe structure, which is undersampled in Fig. 1. These fringes are more marked for co-polarized excitation, where THG and SFG have comparable magnitude.

We have characterized the dependence of such phenomena on the exciting polarizations and on $R$: our main findings are summarized in Fig. 2. The nonlinear conversion is enhanced by two resonances, which are tuned to $\omega$ for about $R = 210\text{ nm}$ and $R = 350\text{ nm}$. These are identified respectively as the magnetic dipole (MD) mode and a first-order anapole, which is a current distribution resulting in interferential cancellation of the scattering to the far-field. Anapoles thus bring about a strong radiation confinement, which has been recently exploited to boost the efficiency of SHG [4] and THG [5] in semiconductor antennas similar to ours. Notably, we find that the SFG at the anapole is up to an order of magnitude more intense for cross-polarized excitation, so that the polarization essentially acts as an ultrafast optical switch. In contrast, SFG at the MD is mostly insensitive to the pump polarizations.

Extensive numerical simulations of the nonlinear response were performed using the finite element method and COMSOL, in order to further validate and refine our interpretation of the experimental data. An excellent agreement with experiment is observed in Fig. 2, both in terms of the dependence of the SFG on $R$ and of its relative amplitude between different resonances and polarizations – except for the co-polarized MD peak, which is too large by a factor 3.

4. Conclusions

We demonstrated that SFG can offer an efficient $\chi^{(2)}$ based frequency-tripling pathway alternative to THG at the nanoscale. The interplay of the resonant modes of the structure underpins a non-trivial dependence of the optical response on the parameters of system and excitation. In particular, the marked dependence on the pump polarization makes the studied system a promising candidate to realize logical elements in miniaturized photonics circuits.

References


Active tuning of thermal radiation in the far-field and near-field range with emerging low-dimensional materials

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Abstract
Controlling the flow of a thermal current is of critical importance for any application that requires thermal regulation and efficient dissipation of heat as well as in energy harvesting systems. Previous approaches have focused largely on modulating thermal conductance via tailoring the propagation characteristics of acoustic phonons. In contrast, in this talk I will discuss means of controlling the flow of heat mediated by infrared thermal radiation. I will discuss how leveraging the unique properties of low-dimensional materials like graphene and monolayer hexagonal boron nitride can yield significant tuning of radiative heat in both the far-field and near-field ranges, with ON/OFF contrast ratios that exceed an order of magnitude.

1. Introduction
Gaining control of thermal transport is typically based on controlling the heat conduction via tailoring the propagation characteristics of acoustic phonons. For this, various phenomena have been investigated, including temperature-dependent phase-change materials, defects and guest ions, mechanical deformations in materials such as polymers and thermoelectrics, to name a few. Nevertheless, with these approaches, the long wavelength of acoustic phonons restricts the down scaling of thermal controllers to the order of micrometers. Furthermore, such thermal modulation schemes report rather modest contrast ratios between the ON and OFF states of a thermal current. It is highly desirable to extend the range of tunability of thermal properties, as well as to miniaturize thermal modulators.

In this talk, I will discuss means of controlling thermal transport via tailoring thermal radiation (photons in vacuum), as opposed to controlling thermal conduction. I will show that such control is possible in both the thermal far-field and near-field, corresponding to distances larger and comparable or smaller than the thermal wavelength, respectively. I will show that one can leverage various properties of low-dimensional materials and heterostructures to achieve significant tuning of thermal emission and corresponding large tunability in the radiative heat transfer between objects at different temperatures.

2. Far-field thermal emission control via phonon polaritons and graphene
In the far-field range, controlling radiative thermal properties reduces to controlling the thermal emissivity of materials and nanostructures. The electrostatically-tunable optical properties of graphene have been extensively investigated for controlling thermal emission. Nevertheless, the response of graphene to radiation is rather weak as well as broadband, whereas a considerable number of applications in thermal switching and energy requires narrowband as well as strongly tunable thermal emissivity.

Following these requirements, recently, significant theoretical work has been devoted on tuning the infrared properties of graphene/dielectric multilayer heterostructures, often termed hyperbolic metamaterials, that are also excellent thermal emitters. Yet, most previous considerations remain theoretical.

I will discuss the theoretical description, experimental realization and characterization of a graphene/polar dielectric multilayer metamaterial [1] (Figure 1 (a)). Combining graphene with a polar dielectric (SiO2/Al2O3) in a heterostructure allows for strongly resonant infrared absorptivity at the Reststrahlen band of the dielectric material. This resonance becomes widely tunable via electrostatic gating, by altering the plasmonic response of graphene. Since, by Kirchhoff’s law, thermal absorptivity equals emissivity, this metamaterial exhibits a far-field widely tunable emissivity. We experimentally achieve significant tuning of graphene’s Fermi level from 0 eV to 0.5 eV, and measure experimentally the corresponding change in the infrared properties of the metamaterial via infrared spectroscopic ellipsometry and Fourier transform infrared spectroscopy.

3. Near-field gate-tunable thermal switching
Gaining control of thermal radiative properties in the nanoscale requires control of near-field radiative heat transfer, mediated by surface polaritons that tunnel through sub-micrometer vacuum gaps. In this talk, I will show that the concept of a metal-oxide-semiconductor (MOS) capacitor, as is widely used in electronic switching, can be alternatively used as a thermal MOS switch that achieves
significant tuning of evanescent photon heat flux via external bias [2] (Figure 1 (b)).

In this case, the oxide material serves a dual purpose of providing a control-channel surface phonon polariton (SPhP), as well as electronic insulation for electrostatic gating. The active material can be a doped semiconductor, a transparent conductive oxide, or graphene, all supporting surface plasmon polaritons (SPP) at infrared frequencies. The resulting contrast ratios of such arrangements are predicted to exceed 200%, referring to the ratio between ON and OFF states that correspond to enhanced and suppressed radiative thermal transport.

4. Deep-subwavelength three-resonator-based thermal switch with strain-tuned hexagonal boron nitride

Finally, I will discuss our recent results in [3], where we present the theory of a three-body-based thermal switch that operates similar to the electronic source-gate-drain transistor. Based on our theory that is founded on the basis of coupled mode theory, we identify the fundamental material requirements that would yield significant thermal tunability. We conclude that low-loss and narrow-band electromagnetic resonances are key for efficient switching of radiative heat. These resonances ought to be tunable via an external mechanism, e.g. temperature-dependent optical properties, phase-changes, optical or electrostatic gating, and mechanical tunability.

In search of a suitable material system for employing our concept of thermal switching, we leverage the low-loss and narrow-band response of monolayer hexagonal boron nitride. We present a study that includes \textit{ab initio} calculations of its dielectric response in the infrared range, which is widely tunable with strain as has been shown in recent experiments. Using fluctuational electrodynamic calculations of the radiative heat transfer between hexagonal boron nitride monolayers (Figure 3 (c)), we show that deep-subwavelength (with dimensions <100 nm) thermal switching is possible with contrast ratios exceeding reaching 98%.

References


\[ \text{Figure 1. (a) A far-field graphene-polaritonic-based tunable metamaterial adopted from [1]. (b) A near-field thermal switch based on metal-oxide-semiconductor structures composed of a gate-tunable material with tunable plasmonic response adopted from [2]. (c) A three-resonator-based deep subwavelength thermal switch based on straining of monolayer hBN.} \]
Diagnostic Colorimetric Metasurfaces Visualize Disease in Fibrous Biological Tissue

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Abstract
We leverage the unique properties of anisotropic, colorimetric metasurfaces to scale down the complex manipulation of light and selectively visualize disease-relevant fiber density and orientation in biological tissue. Ranging from Alzheimer’s disease to heart disease, fibrosis or cancer, we discuss the potential of metasurfaces to yield rapid, precise, low-cost diagnostics.

1. Introduction

The origin and progression of a variety of leading health challenges, encompassing Alzheimer’s disease, heart disease, fibrosis and cancer, are directly linked to changes in the presence and orientation of fibrous matter in biological tissue. Fibrous biological tissue exhibits distinct anisotropic optical properties, which can be leveraged for selective imaging. However, these naturally occurring light-matter interactions are inherently weak, posing barriers to their visualization in a clinically translatable manner. Here,1,2 we leverage anisotropic, colorimetric metasurfaces to selectively visualize disease-relevant fiber density and orientation in biological tissue. Starting with the example of breast cancer diagnostics, we then expand our view to the rich palette of fiber-affecting diseases where metasurfaces hold great potential to achieve rapid, precise and low-cost tissue diagnostics with facile clinical implementation.

As an illustrative example, we focus on breast cancer diagnostics, a disease affecting hundreds of thousands of patients in the United States annually. While the accurate determination of disease stage is closely linked to the probability of patient survival, current diagnostic technology presents patients and physicians with trade-offs between duration, precision and cost. Here, we present an all-optical, label-free technology for quantitative, real-time cancer tissue diagnostics on a single, clinically-compatible chip. Periodically-arranged sub-wavelength dielectric nanostructures, are patterned into dielectric layers on glass microscope coverslips to form metasurfaces, where biopsied tumor tissue sections can be deposited following routine clinical procedure. Specifically, our technique maps the anisotropy and orientation of collagen fibers, a quantitative marker of cancer stage in tissue, onto metasurface structural color.

We pattern a sub-wavelength rectangular lattice of rhombohedral perturbations into stacked layers of silicon nitride (215 nm) and silicon dioxide (75 nm), where < 10 nm bandwidth guided-mode resonances yield a high-purity chromaticity in reflectance, with a polarization-sensitive colorimetric response. With full-field numerical simulations, we demonstrate how selective tuning of the guided-mode resonances maps the orientation angle of collagen fibers onto blue-to-green chromaticity, while changes in refractive index are separately mapped onto red-to-green chromaticity as the sensing medium varies from air to biological tissue. For breast cancer diagnostics, where the presence and orientation of collagen fibers at the tumor margin can distinguish early-stage from metastasized disease, we quantify the performance of our metasurface via the 1976 CIE Lab color discrimination. We find that our metasurface outperforms polarized light microscopy by unambiguously mapping tissue orientation onto structural color at higher color discrimination values, while enabling the distinction of orientation angles which otherwise yield an identical response. This improved performance is attributed to engineered symmetry-breaking of the metasurface geometry by Stokes-parameter-analysis of the metasurface-reflected fields.

Finally, we experimentally characterize the anisotropic optical properties of planar sheets of ordered synthetic collagen scaffolds using both conventional polarimetry and
our metasurface device. Working at the interface of nanoscale optics and medicine, our colorimetric metasurface platform has the potential to set a new benchmark for rapid, quantitative and cost-effective diagnostics for a range of fiber-affecting diseases.

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References


Space-time metamaterials: homogenization theory, giant bianisotropy and light drag without moving media

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Abstract
Here I will present a theory of homogenisation of space-time metamaterials, which yields expressions for the effective permittivity, permeability and magnetoelectric coupling in the long wavelength limit. The derived parameters show that synthetic motion can result in giant bianisotropy and the dragging of electromagnetic fields down to the quasistatic limit and without any moving matter.

Introduction
Recently, time has emerged as a new degree of freedom for metamaterials, as variations of the electromagnetic parameters in time as well as in space allow for new pathways in wave control. In these time-dependent systems, energy is not necessarily conserved, and the linear bias imposed by travelling wave modulations permits non-reciprocal effects in the absence of external magnetic fields. In this contribution I will present a theory of homogenisation of space-time metamaterials, which provides analytical expressions for the effective permittivity, permeability and magnetoelectric coupling in the long wavelength limit [1]. From the derived parameters I will show how it is possible to bring nonreciprocity down to zero frequency if both the permittivity and permeability are modulated, and how the synthetic motion present in these systems enables a Fresnel drag effect of light without any moving matter [2]. Thus, giant and tunable magnetoelectric effects emerge without external magnetic biases or relativistically moving matter. Our theory unveils a regime where the modulation speed approaches that of waves in the background medium where homogenisation breaks down and a new mechanism for gain emerges [3], enabling a form of nonreciprocal broadband amplification that could be realised in graphene [4]. On the other hand, temporal only modulations enable novel ways to excite surface waves from the far field [5].

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References
Near-field directionality with higher order multipolar sources

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Abstract

We reveal the near-field directionality properties of multipolar sources comprised of superpositions of electric and magnetic dipoles and quadrupoles. We build a table of elementary sources comprised of the superposition of two multipoles, either both electric, both magnetic or one of each nature.

1. Introduction

Point sources, such as electric and magnetic dipoles, have sparked a burst of interest in recent years due to the ease of achieving them, for example via plane wave scattering off nanostructures, and for their potential to be integrated in photonic circuits, thanks to their reduced dimensions. Circular electric and magnetic dipoles, together with the combination of linear and circular electric and magnetic dipoles, have been exploited to achieve tailored directionality in near and far fields [1]. This is the case, for example, of sources known as Huygens and Janus dipoles [2, 3, 4], whose symmetries result in selective coupling to guided modes, when they are placed in close proximity to a waveguiding structure.

Dipolar responses are the first order approximation of the scattering from nanostructures and, for objects which are significantly smaller than the wavelength, the only relevant contribution to the overall scattering cross section. However, this is not necessarily the case when moving towards smaller wavelengths or bigger structures, in which the electric and magnetic quadrupolar Mie resonances of the nanoscatterer are non-negligible and, in some wavelength range, overpowering the dipolar responses. The presence of quadrupolar responses provides us with several novel degrees of freedom which can be exploited to tailor the near- and far-field coupling of the source. While the dipolar sources only possess three degrees of freedom each, corresponding to the Cartesian components of the electric or magnetic dipole moment, the quadrupole moment is a $3 \times 3$ tensor, with 5 independent components. Each of these components represents an extra degree of freedom which can be exploited when tailoring the spectrum of the source.

2. Discussion

The coupling of an electromagnetic source to a planar waveguide can be analytically predicted by looking at the source’s angular spectrum. The coupling amplitude and phase, in fact, corresponds to the angular spectrum of the source scaled by a transfer function. This means that any zero in the angular spectrum of a source, corresponding to a specific point in the momentum space, will remain a zero after the transfer function is applied [1]. In momentum space, a waveguide possesses a dispersion relation, which determines the wavevector of the mode excited in the waveguide at any given frequency. This means that, engineering the angular spectrum to have a zero in momentum space corresponding to the specific wavevector supported by the waveguide at that wavelength, one can ensure the complete absence of excitation of that mode via the specific source. This simple idea is behind the whole engineering of multipolar electromagnetic sources we are presenting. Placing the source along the z-axis in $z = z_0$, we can write, in the $k_x - k_y$ plane, the angular spectrum of the source, potentially being a superposition of electric and magnetic dipoles and quadrupoles, as a function of the multipole moments:

$$E(k_x, k_y) = f(p, m, Q_E, Q_M),$$

where $p$ is the electric dipole moment vector, $m$ is the magnetic dipole moment vector, $Q_E$ is the electric quadrupole moment tensor and $Q_M$ is the magnetic quadrupole moment tensor. Each of the components of these vectors and tensors provides us with a degree of freedom that we can use to solve a system of equations in which we specify a specific amplitude and phase for the angular spectrum at each point in $k$-space that is relevant to our problem. In this way, for example, we have engineered the excitation of a single directional mode with the source placed between two identical waveguides, as can be seen in Figure 1. That has been achieved using a superposition of an electric dipole and an electric quadrupole, imposing the angular spectrum to be equal to zero for the wavevectors of the three guided modes which are not excited by the source. Between the same two waveguides, a Huygens dipole would excite two guided modes, propagating in the same direction, one in each waveguide. A Janus dipole would also excite two modes, this time propagating in opposite directions in the same waveguide. This approach is very general and can be applied to any superposition of multipoles. Our theory allowed us to find Huygens-like and Janus-like solutions, to show that we can realise the same excitations that were previously obtained with an electric and a magnetic dipole but using instead the superposition of different multipoles. We have also found solutions predicting the excita-
Figure 1: Electric field amplitude of a superposition of an electric dipole and an electric quadrupole. The relative amplitudes and phases between the dipole and the quadrupole moment components follow the relations:
\[ p_x = \frac{-in}{\kappa}, \quad q_{xx} = \frac{2\pi n}{\kappa}, \quad q_{xz} = \frac{3}{\kappa}, \]
where \( n \) and \( \kappa \) are related to the wavevector \( \mathbf{k} \) via \( \mathbf{k} = \mathbf{k}_0(n, 0, i\kappa) \). This superposition gives rise to the directional excitation of a single mode between two waveguides supporting two guided modes each. The waveguides, in fact, are metal slab with \( \varepsilon = 2 + 0.1i \), each of which can support guided modes going to the left and to the right. The angular spectrum of the multipolar source has been engineered so that it couples to only one of the four possible modes in the system, leading to unidirectional and side-selective excitation.

A unidirectional excitation of a single guided mode, such as those seen in Figure 1, clearly possible because of the extra degrees of freedom which were not available with two dipoles only. This study forecasts the possibility of a precise engineering of the relative amplitudes and phases of several guided modes at the same time, owing to the vast number of degrees of freedom available compared to the previous realisations limited to the dipolar case.

References


Near-Field spectroscopy of Photonic Crystal Cavities characterized by Fano Local Density of States

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Abstract

Microcavities and nanoresonators are characterized by their quality factors (Q) and mode volumes (V). While Q is unambiguously defined, there are questions on V and, in particular, on its complex-valued character, whose imaginary part is linked to the non-Hermitian nature of open systems. The complex modal volume implies a deep revision of the Purcell factor expression, with counterintuitive effects, such as non-Lorentzian local density of states. We experimentally demonstrate these predictions in coupled photonic crystal cavities with low optical losses.

1. Introduction

Optical resonators play an essential role in current developments in nanophotonics, such as integrated photonics, optical sensing, metamaterials and quantum electrodynamics. The interaction of light with electromagnetic resonators fundamentally relies on the resonant modes of the structure. With the recent advent of theoretical results on the normalization of leaky resonator modes, it becomes evident that cavity perturbation theory cannot rely on normalization based on energy but a quasi-normal-mode (QNM) formalism is essential to account for the non-Hermitian character of the problem in the presence of non-negligible energy dissipation [1, 2]. QNMs are formal solution of differential equations with complex eigenvalues. Regrettably, the complex eigenvalues cause mathematical difficulties with QNM normalization. One approach to avoid the normalization problem imposes to consider energy dissipation as a perturbation of an ideal closed and non-absorbing system. With this approach the system is Hermitian and admits a complete set of discrete normal modes with real eigenvalue. The perturbation just results in a broadening of the eigenstates with a Lorentzian line shape, but not in a change of the resonance frequencies and field distributions. It has been showed that this phenomenological approach work properly for resonators with small energy dissipation (i.e., a high quality factor), but it becomes largely unsubstantiated for less confined resonances characterized by low quality factors. Non-Hermitian theories also predict that the complex nature of V leads to a strongly non-Lorentzian spectra profile of the local density of states (LDOS) in peculiar photonic and plasmonic systems [1, 2]. In coupled resonators, the spectral dependence of the Purcell enhancement is predicted to be a generalized Fano profile with a dip in the spectral line shape [1]. Here, we experimentally demonstrate LDOS with strong non-Lorentzian line shapes in pairs of coupled, high-Q and small-V photonic crystals cavities (PhCCs). We show that the LDOS spectral line shape and spatial distribution can be measured by near-field hyperspectral imaging.

2. Material and Methods

We investigate two coupled L3 cavities in a GaAs slab with very different losses, see Fig. 1(a). Cavity #1, located near the border of the 2D photonic crystal, has $Q_1 \sim 400$, on the contrary cavity #2 has $Q_2 \sim 6000$. The diameter of the air holes circled in blue is tuned to control the losses of cavity #1, while the diameter of the air holes circled in red is tuned to reach a nominal detuning $\Delta = (\omega_1 - \omega_2)/|2g| \sim 0$, with g the coupling constant between the two uncoupled cavities and $\omega_1$ and $\omega_2$ their frequencies. In the middle of the GaAs membrane high-density InAs QDs are embedded. If properly excited, the InAs QDs show at room temperature bright photoluminescence (PL) which acts as an internal light source for the photonic structures. The measurements are performed with a scanning near-field optical microscope (SNOM) in illumination/collection geometry, was used. The spatially resolved images were recorded by scanning the probe tip over the sample at a fixed distance (few tens of nm).
The sample is excited by a laser diode at 780 nm, coupled into the tip. The emitted PL signal, collected by the tip, is coupled to a spectrometer and is finally detected by a liquid nitrogen cooled InGaAs array. At every tip position, the entire spectrum of the sample is collected with a spectral resolution of 0.1 nm.

3. Results

The near-field PL spectra collected in cavities 1 and 2 are reported in Figs. 1(b) and 1(c), respectively. As predicted by the QNM model, we observe that the LDOS in cavity 1 has an evident non-Lorentzian shape. Data are well described by the QNM formalism as the sum of two Fano profiles [blue and red lines are fits from the theory and the dark yellow and green lines are the mode decomposition in Fano profiles]. The fits in Figs. 1(b)–1(c) reproduce well the data and unveil the possibility for resonances to have negative contributions to the LDOS. To our knowledge, this constitutes the first experimental demonstration of strong non-Lorentzian LDOS of individual photonic resonances [3].

The observed Fano-like lineshape represents a distinctive hallmark that allows to directly relate the spectrum locally collected by the SNOM tip to the electric LDOS of the investigated system. In Fig. 2 are reported finite difference time domain (FDTD) simulations of the coupled system. The LDOS spectrum can be obtained as the flux of the Poynting vector (S) through a box that contains the exciting dipole, or through the calculation of the imaginary part of the Green’s function, which are reported with dashed lines and open circles, respectively, for three different tip positions on the sample. The relevant aspect in Fig. 2 is that the lineshape of the LDOS strongly vary over spatial distances below the diffraction limit, calling for the use of near-field techniques for LDOS mapping. In order to benchmark this prediction, one has to consider the SNOM physical mechanism that converts the near field into the far field. With dielectric tip, it is possible to argue that the scattering in the far-field is due to the induced macroscopic polarization of the glass forming the apex of the tip. The induced dipoles inside the tip, which produce the detected light scattering in the far-field, are proportional to the inducing electric near-field of the PL emission at the position of the tip. This means that the signal collected by the SNOM tip is proportional to PL electric field intensity $|E|^2$ and averaged over the spatial extension of the tip. Therefore, in the three graphs is also reported the electric field intensity on the small square sensors, that reproduce different tip positions. The very good agreement of the spectra of $|E|^2$ with the LDOS confirms that SNOM spectroscopy is able to direct image the LDOS with a deep-subwavelength resolution of the order of 100 nm.

4. Conclusions

We provide experimental evidence of the existence of Fano LDOS in coupled system composed by two PhCCs with unbalanced loss, where one of the two PhCC has a relatively high nominal Q of 6000. We also prove that Near-field hyperspectral imaging of quantum dot photoluminescence is a direct tool for measuring the line shape of the LDOS.

Acknowledgements

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References

Metal-Insulator-Metal cavities for light enhancement and modulation

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Abstract

We show that Metal-Insulator-Metal (MIM) nanocavities that sustain epsilon-near-zero (ENZ) resonances constitute a versatile platform for light modulation and amplification in the visible spectral range. These systems can be seen as optical quantum wells for photons, and using an analogy to quantum mechanics facilitates the analytic prediction of the resonance frequencies. The single cavity can be configured to manifest light absorption close to 100% at a given wavelength. Coupling MIM cavities extends the tunability of the resonances, and we demonstrate how a MIMIM system can be configured to enhance both the absorption and emission of a dye layers on the top of it. Incorporation of the emitting material inside the dielectric cavity of a MIM system allows to control directionality and polarization of the emitted light. Finally, the approach can be extended to multiple cavity layers that form ENZ bands, which can be described by the Kronig-Penney model.

1. Introduction

Layered Metal-Insulator-Metal (MIM) structures provide an interesting and highly versatile platform for light manipulation. Using thin dielectric layers, with thicknesses well below the $\lambda/2$ condition, and with momentum transferring excitations they can function as plasmonic waveguides. [1, 2] Recently, we have demonstrated that in the regime of slightly thicker dielectric layers, this system acts as a photonic cavity sustaining ENZ resonances. [3] The semiclassical approach that we outline allowed then to describe the double cavity in a MIMIM system as a coupled double quantum well. [4] The possibility to tune the splitting of the two low-energy cavity resonances via the thickness of the central metal layer can be used to overlap them with the absorption and emission bands of a thin film of perovskite nanocrystals that was spincoated on top of the structure. In this architecture the interaction of the emitters with the ENZ modes enhanced absorption and emission of the nanocrystal layer, quantified by an increased radiative rate. Ultimately, toward strong light matter coupling, it would be desirable to place the emitting layer inside the dielectric cavity where the field enhancement is strongest. We worked with push-pull chromophores, for which the refractive index can be controlled to be similar to that of the dielectric layer (Al$_2$O$_3$). [5] That allowed to transfer the directional and polarization properties of the MIM cavity to the emission of the organic dyes.

2. Results & Discussion

In this work, we will show how the concept of MIM cavities seen as quantum wells for photons can be extended to build ENZ bands in multiple quantum wells. [6] We fabricated a layered metal-insulator structure with 5 coupled quantum wells and measured its properties with spectroscopic ellipsometry. The results are in very good agreement with scattering matrix methods (SMM) simulations. We extend our semiclassical model to the multi-cavity structure, developing analogies to quantum systems with multiple states. The Kronig-Penney modeling of the multilayer can furthermore elucidate the boundary between the photonic ENZ bands and hyperbolic metamaterials.

3. Conclusions

MIM cavities constitute ultrathin optical cavities with resonances in the visible range that can be fabricated without the need of nanostructuring by lithography processes.
Therefore, they can be implemented on large areas by cost-efficient thermal deposition methods. This platform allows to fabricate superabsorbers, optical cavities for light emission enhancement and modulation, and can provide active elements in ultrafast signal processing.

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References
Solar light with sub-microns hyperboloids non-imaging light concentrators arrays

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Abstract

Metamaterials based on arrays of subwavelength dielectric structures have recently proved to be a viable research tool towards the realization of various photonic devices. In the current study we introduce a new approach towards efficient light trapping and broadband absorption of solar radiation based on silicon surface arrays composed of subwavelength trumpet non-imaging light concentrators (henceforth, trumpet arrays). In geometrical optics, a three-dimensional trumpet non-imaging light concentrator is a hyperboloid of revolution with an ideal light concentration ratio. We use finite-difference time-domain electromagnetic calculations to examine the optical response of an infinite cubic-tiled substrate-less silicon trumpet array under normal illumination. The absorptivity spectra of trumpet arrays are characterized by strong absorption peaks, some of which are just below the Yablonovitch limit. The enhanced light trapping is attributed solely to the efficient occupation of the array Mie modes, and we show absorption enhancement at near infrared that is an order of magnitude higher than that of the optimized nanopillar (NP) arrays. We show superior broadband absorption of solar radiation in trumpet arrays (with unoptimized geometry) compared with that of the optimized NP arrays (~26% enhancement). The higher optical absorption in the trumpet array is governed by low transmissivity, in contrast to the NP array in which the absorption is governed by low reflectivity. Finally, we show that low reflectivity in trumpet arrays is governed by modal excitation at the upper part of the trumpets (which is also supported by the weak dependency of the reflectivity on the array height), whereas the transmissivity is governed by modal excitation at the lower part of the trumpets.

Keywords:
hyperboloids concentrators, light trapping, nanopillar arrays, broadband absorption, photon management.
Photonics with Metallic Alloys

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Abstract
We propose metallic alloys and intermetallic materials as a platform to control the electromagnetic spectrum in the UV-NIR range. Opportunities for developing optical components using metallic materials beyond noble metals for energy harvesting and superabsorption applications will be discussed.

1. Introduction
The capability of controlling the optical response of metals has allowed the progress of optical devices varying from color pixels for displays to superabsorbers. Recently, the need for dynamic devices with tunable functionality has prompted the search for materials and architectures, with optical reconfigurability. Most strategies achieving reconfigurability are centered on altering the materials’ electrical and/or optical properties, including the application of bias, light polarization, and strain. Regarding materials usually employed in reconfigurable photonics, most tactics are based on VO$_2$, where a change in temperature of >40 °C is responsible for the transition between a dielectric (low temperature) and a metal (high temperature). Very recently, changes in chemical composition have also been shown to enable reconfigurability. In particular, the hydrogenation of Mg capped by a Pd layer has been recently demonstrated to be an effective knob for color tunability, resulting from the reversible shift between Mg (metallic) and MgH$_2$ (dielectric behavior) upon hydrogenation and dehydrogenation.

2. Results and Discussion

2.1. Magnesium for transient photonics
We show a new material system for transient photonics based on Mg (metal) and MgO (dielectric), earth-abundant and CMOS-compatible. We demonstrate scalable color pixels shaped by metal–insulator–metal (MIM) thin films formed by Mg/MgO/Mg, where vivid colors disappear in less than 10 min when exposed to water, at room temperature and neutral pH. These pixels, with intense chromaticity, are a consequence of constructive interference and can include the entire color gamut, from blue to burgundy, depending on the thickness of the MgO dielectric MgO layer [1]. Our results display that the full standard red green blue (sRGB) color space diagram can be attained. This scalable thin-film deposition and the low-cost materials utilized are ideal for coating applications. The dynamic behavior of the color pixels is confirmed by etching the MIM structures in water, under ambient conditions, as shown in Figure 1. All colors disappear in minutes upon samples’ exposure to water. We provide a detailed analysis of role of water temperature and thin film deposition method on the etching rate [2]. The MIM pixels are omnidirectional with respect to color up to 40 degrees and provide bright colors up to 80 degrees. Our findings are relevant for encryption.

Fig. 1: Photographs of Mg/MgO/Mg color pixels with 1 in.$^2$ area covering the full chromaticity gamut as it dissolves in water, at room temperature (23 °C) and neutral pH [1].

2.2. Hydrogenation for dynamic photonics
Pd$_x$Au$_{1-x}$ alloys are a promising alternative for next-generation optical hydrogen sensors. They present high
chemical durability and optical sensitivity to small amounts of hydrogen gas. Yet, the relationship between their optical response and chemical composition is currently not fully understood. We investigate the dynamic optical behavior of thin film PdxAu1−x in situ by ellipsometry as they are exposed to H₂. We show dynamic optical response upon hydrogenation. PdxAu1−x displays the strongest optical sensitivity to H₂ in the near infrared region of the electromagnetic spectrum. An optical hydrogen response as low as 34% Pd is measured, indicating that film stress and microstructuring are critical in the sorption behavior. We propose the implementation of PdxAu1−x as grating structures and as a planar physical encryption scheme, where dramatic changes reflectivity is observed upon hydrogenation.

The superior optical behavior of metallic alloys will also be presented in the context of catalysis (Pd-Au [4]), superabsorbers (Al-Cu [5]), NIR photodetectors (Au-Ag [6]), among other applications [7-10].

### 3. Conclusions

In summary, metal alloys have recently emerged as an alternative material for photonics due to its tailored, on demand optical properties. We demonstrated that permittivity values not achievable by noble metals can be obtained by the binary mixture of Au, Ag, Cu, and Al. Moreover, we have shown the near-unity (> 99%) absorption of thin-film formed Si/AlCu stacks. To elucidate how the optical behavior of the metal alloys differs from the linear combination of their pure counterparts we calculate their band structure by DFT, and identify the individual contribution of each metal.

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### References

Light-absorption in nano-antennas: from self-heating to reconfigurable metasurfaces

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In the last decade, optical nanoantennas have revolutionized light manipulation and control at the nanoscale. Light absorption was initially considered a purely detrimental process, reducing the efficiency of optoelectronic devices. Recently, however, it has attracted growing interest, enabling novel light-energy conversion pathways and offering intriguing opportunities for reconfigurable systems.

In the first part of the talk, I will discuss self-induced optical heating effects in highly absorbing Silicon (Si) and Germanium (Ge) nanoresonators. In particular, I will show recent calculations demonstrating that, due to thermos-optical effects, self-heating can give rise to a complex, non-linear relationship between illumination intensity and temperature, even for moderate illumination intensities relevant for applications such as Raman scattering [5]. Subsequently, I will discuss how self-induced optical heating could be employed in optical devices and metasurfaces. In the second part of the talk, instead, I will discuss the opportunities of localized heating through metallic (plasmonic) nanoantennas. In particular, I will present our recent efforts in reducing the computational cost of photothermal energy dissipation in 3D arrays of nanoparticles and I will discuss the ensuing opportunities for material optimization.
Large-area optical metasurfaces: from plasmonic color routing to energy harvesting in 2D materials

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Abstract
The nanofabrication of nanoscale metasurfaces able to feature tunable optoelectronic response is crucial in view of sensing and flat-optics applications. Here the engineering of large-scale metasurfaces based on self-organized plasmonic nanostripe antennas will be demonstrated. These templates enable accurate tuning of localized plasmon resonances and can feature broadband color routing properties with strong impact in flat-optics, photonics and sensing applications.

1. Introduction
The engineering of metasurfaces based either on plasmonic nanoantennas or on atomic two-dimensional (2D) materials is currently a very active field of research with a strong impact in optoelectronics, sensing, and nanophotonics [1,2]. A recent trend in the field aims to increase the complexity of lithographically designed metasurfaces for flat-optics and optical spectroscopies. However, in order to scale-up these promising configurations to real-world applications, alternative large-area approaches are attracting increasing attention. Here we demonstrate the engineering of large-scale metasurfaces based on self-organized plasmonic nanoantennas. The plasmonic response of self-organized arrays of nanoantennas is optimized and tuned for biosensing and colour routing applications, while flat-optics MoS₂ nanogratings are developed for broadband photon harvesting applications.

2. Results and discussion
Self-organized plasmonic metasurfaces are fabricated with a novel approach exploiting the ion beam induced wrinkling in glass substrates for the synthesis of transparent faceted nanopatterns, extending over a large area (cm²) [1]. These templates are ideal for confining quasi-one dimensional (1D) arrays of plasmonic nanostripes (Fig. 1a) with a maskless approach. Controlled tuning of localized plasmon resonances from the visible to the Near- and Mid-IR has been achieved by tailoring nanoantennas shape and/or polarization, thus demonstrating competitive Surface Enhanced IR Absorption (SEIRA) performances for these large-scale templates [2]. A multi-step variant of the same self-organized method has recently enabled the engineering of a novel flat-optics configuration based on bimetallic cross-polarized nanoantennas (Fig. 1b). These plasmonic templates feature broadband color routing functionalities with superior light scattering directivity, and results to be very promising in scalable flat-optics applications [3,4].

Figure 1: a) Self-organized plasmonic nanostripe arrays (top-view SEM image), and b) bimetallic nanostripe dimers (cross-section SEM image).

3. Conclusions
In conclusion, we demonstrated the self-organized engineering of anisotropic arrays of plasmonic nanoantennas supporting tunable plasmonic response and near-field enhancement for sensing. We have shown the possibility to engineer bimetallic antennas featuring directional light scattering, paving the way for color routing in novel large-scale flat-optics components.
Acknowledgements

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References


Time-Resolved Cathodoluminescence in a Transmission Electron Microscope

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Abstract

Time resolved Cathodoluminescence (TR-CL) is a unique technique that allows to measure the lifetime of radiative transition down to the picosecond at the nanometer scale. In this presentation, we will discuss the first experimental demonstration of TR-CL in a transmission electron microscope. We will show its potential, and the opportunities offer by its complementarity with other electron based spectroscopies, to correlate the optical and structural properties of materials.

Summary

The study of the optical properties of III-V heterostructures at the nanometer scale now routinely takes advantage of cathodoluminescence (CL) spectroscopy. This technique studies the luminescence of materials after their excitation by high energy electrons. Cathodoluminescence and photoluminescence spectra being quite similar, therefore CL is usually considered a nanoscale equivalent of photoluminescence. Performed in an electron microscope, CL can also benefit from the wealth of other electron-based spectroscopy techniques available (X-ray, Secondary electron, EELS, …) and give access to a precise correlation between the optical and structural properties. If cathodoluminescence is now commonly used in nano-optics, most measurements do not get access to the temporal dimension.

The development of time-resolved Cathodoluminescence (TR-CL) in a scanning electron microscope (SEM) enabled the measurement of the lifetime of excited states in semiconductors with a sub-wavelength spatial resolution. It was used for example to measure the influence of stacking faults on the GaN exciton lifetime [1], to probe the role of a silver layer on the dynamics of a YAG crystal [2] or to show the influence of stress on the optical properties of ZnO nanowires[3]. These results demonstrate that TR-CL is essential to study the correlation between semiconductor optical and structural properties (composition, defects, strain…). Despite giving unvaluable information, TR-CL in a scanning electron microscope is still limited in spatial resolution. CL in the transmission electron microscope (TEM) proved to dramatically improve the spatial resolution with respect to SEM-CL, and gave access to multiple complementary analysis tools (from atomic scale imaging to electron energy loss spectroscopy). The advent of the yet undemonstrated TR-CL in a STEM is therefore expected to be a major next step for the investigation of the optical properties of nanomaterials.

In this presentation, we will discuss our first experimental demonstration of time-resolved cathodoluminescence within a transmission electron microscope. These experiments were performed in a unique femtosecond pulsed transmission electron microscope, with a cold-FEG electron gun [4]. This technology allows among other things sub-ps temporal resolution while preserving a spatial resolution of a few nanometers, essential for the study of nanophotonic materials. We will present the first lifetime maps acquired in a TEM both on nano-diamonds and InGaN quantum wells and discuss the unique features and opportunities of this technique.

References

Gyrotropic responses mediated by Jahn-Teller and spin-orbit interactions

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Abstract
We report on gyrotropic responses mediated by Jahn-Teller polarons and spin-orbit coupling, whereby a spin-reversal is induced by photons and can be selectively detected by circularly polarized light. We show that spin-reversal requires the concurrent action of orthorhombic and tetragonal Jahn-Teller modes, which opens up a pathway to explore quantum effects that involve spin and orbital degrees of freedom. Additionally, as magnetic polarons are ubiquitously inherent to many strongly correlated systems, our results provide an original, general pathway towards the generation of magnetic-responsive gyrotropic responses that may open novel avenues for magnetoelectric coupling beyond the conventional modulation of magnetization.

1. Introduction
In transition metal oxides, a subtle balance between different competing electronic and structural energy scales leads often to a complex phase diagram. One paradigmatic case is that of colossal magnetoresistance (CMR) oxides, in which the magnetic structure and electrical conductivity can be largely modified by magnetic fields, temperature or strain. Here we focus on the magneto-optical response of CMR manganites, which arises when polarized light interacts with magnetic materials. The magneto-optical activity is caused by changes in polarization state of light, so that a rotation or ellipticity is induced proportional to the magnetization. These changes in polarization are nowadays exploited commercially to control the flux of light along optical fibers, in devices such as optical circulators and rotators. However, these are generally bulky, and inappropriate for integrated electronics. This is the reason why there is large interest to increase the magneto-optical activity beyond the conventional modulation of magnetization.

2. Results and discussion
In this work, we uncover a novel physical mechanism by which the magneto-optic activity is enhanced in optimally doped ferromagnetic manganites [3]. The phenomenon is related to the specific magneto-optical response of polarons, which gives an extra contribution to that of the Drude-like response of delocalized electrons. The emergence of polarons alters locally the electronic structure, so that the magneto-optical activity is increased by more than one order of magnitude around the ferromagnetic transition. This phenomenon is only observed for a relatively narrow range of wavelengths and temperatures.

The gyrotropic response is observed through an anomalous magneto-optical response in La2/3Ca1/3MnO3 films [3]. We have measured the transverse Kerr signal δK, which decomposes into gyrotropic δKg and nongyrotropic δKng terms, which correspond, respectively, to spin-preserving and spin-flipping hopping [3-5] (Figure 1). The mapping of δKng and δKg as a function of temperature and frequency reveals two peaks for the nongyrotropic response located at ℏωKg≈1.9 eV and ℏωKng≈2.7 eV, respectively, while a gyrotropic response only arises around the latter. The gyrotropic response is also observed through polar Kerr measurements [3].

We present a theoretical model in which the amplification of the gyrotropic response is explained in terms of spin-reversing polaron jumping induced by photons of high enough energy, through the concurrent action of spin-orbit coupling and Jahn-Teller vibrations. In contrast, lower energy photons that do not change spin do not induce the gyrotropic enhancement.

3. Conclusions
We have unveiled an unexpectedly large magneto-optical response mediated by Jahn-Teller modes and spin-orbit coupling. Interestingly, the showcased material is La2/3Ca1/3MnO3, for which the extraordinary gyrotropic response is observed near room temperature. The observed optical phenomenon gives an added functionality –unseen previously in any manganite or other magnetic oxides– and puts a new perspective on applications.

On the other hand, our results also show potential for exploring fundamental physics. In particular, we show that for a certain range of temperatures and wavelengths both orthorhombic and tetragonal Jahn-Teller modes are active. This opens interesting perspectives for fundamental physics, related to the orbital physics of the e ⊗ E problem, which could give rise to pseudorotational degrees of freedom, akin to spin-1/2 systems [6].
Figure 1: Temperature dependence of the Kerr ellipticity ε measured at different wavelengths. Around the Curie temperature (T_C) a remarkable gyrotropic enhancement is visible for wavelengths close to blue-violet. This enhancement is not visible for wavelengths in the red part of the visible spectrum. The gyrotropic increase is due to spin-reversal photoinduced hopping driven by photons of large enough energy (inset).

Acknowledgements

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References

Interplay of Absorption and Scattering in Metal-Dielectric Cylinders: Extreme Refractive Index Limits and Response Sensitivities

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Abstract

Structural singularities such as sharp corners are linked to extreme field concentration and presence of hotspots in small particles, typically resulting in enhanced absorption efficiency. In this work we analytically investigate the interplay of absorption and scattering in a class of singular metal-dielectric particles in the shape of joined half-cylinders. We will discuss the role of refractive indices and material loss in the response of these geometries and pinpoint several phenomena including resonant scattering/absorption, sharp absorption response, and invisibility.

1. Results and Discussion

The ability of nanoparticles to shape the scattering and absorption spectra at the nanoscale have established them as a popular choice for several applications in sensing, energy harvesting, biomedicine, and nonlinear optics. In particular, plasmonic nanoparticles enable exceptionally high localized field enhancement close to their resonance frequency (compared to their dielectric counterparts), giving rise to enhanced absorption and scattering responses. These qualities have been found suitable to build compact and efficient modulators, emitters, harmonic generators, and detectors [1], [2].

The local field enhancement in nanoparticles is linked with an enhanced absorption and/or scattering effect. Looking at a typical subwavelength plasmonic sphere or cylinder, in the proximity of the resonance frequency absorption and scattering follow comparable Lorentzian line shapes, with the maximum extinction attainable at the resonance frequency (i.e., when the real part of the permittivity of the particle is close to -2 in a sphere or -1 in a cylinder). Depending on the size and the dispersion properties of the constituent material, scattering or absorption may dominate the overall response of the particle under illumination. Fig. 1 illustrates two generic examples of cylindrical particles illuminated with plane waves propagating normal to the axes of cylinders. The red arrow shows the incident electric field vector and cases of silver (Drude model with $\varepsilon_m = 5$, $f_p = 2175\text{THz}$, and $f_s = 4.35\text{THz}$ [3]), and gold (Drude model with $\varepsilon_m = 1.53$, $f_p = 2069\text{THz}$, and $f_s = 17.65\text{THz}$ [4]) particles are considered. Particle diameters are set at 30 nm and 40 nm and the dipolar responses are calculated at the quasi-static limit.

![Figure 1: Scattering efficiency (blue) and absorption efficiency (red) of plasmonic cylindrical particles with diameter “d”. The gray lines indicate the theoretical limit for the absorption efficiency in each case. Inset of the first panel shows the particle configuration and the incident electric field.](image)

As expected, by decreasing the particle size, a small redshift and spectrum narrowing is observed [5]. Note that in all cases, scattering dominates the overall response of the particle and by decreasing the particle size the absorption contribution may only be slightly increased. To achieve control over the contribution of scattering and absorption, we investigate a variation of cylindrical particles with geometrical singularities as shown in Fig. 2. Previous studies [6]-[9] have shown that certain singular plasmonic geometries (such as touching cylinders, joined half-cylinders, radially anisotropic spheres, etc.) can produce a broadband absorption spectrum, associated with adiabatic focusing of the electromagnetic energy toward the
singularity, providing a rich platform to control scattering and absorption efficiencies, as well as their ratio. We consider the case of joined half-cylinders (Fig. 2, inset). Field distribution around the singularity points strongly depends on the local refractive indices [6], accordingly establishing the far-field response. Fig. 2 illustrates two examples of joined half-cylinders (gold/air and gold/silicon dioxide) where the particles are illuminated with plane waves propagating normal to the axes of cylinders. The red arrows show the incident electric field vectors.

![Diagram](image)

Figure 2: Scattering efficiency (blue) and absorption efficiency (red) of joined half-cylinders with diameter set at d=40 nm. The gray lines indicate the theoretical limit for the absorption efficiency. Inset of each plot shows the particle configuration and polarization of the incident electric field.

Adding geometrical singularities significantly alters the scattering and absorption spectra of the new hybrid particles. Notably, using the same lossy material (i.e., gold), larger overall absorption efficiency is attainable. In addition, unlike their cylindrical counterparts in Fig. 1, it is possible to control the ratio between scattering and absorption, allowing to have regions of frequency where absorption dominates the overall response.

An interesting observation can be made by inspecting the level of absorption and scattering compared with their corresponding theoretical limits. The gray lines in Figs. 1 and 2 indicate the maximum attainable absorption in the dipolar limit: \( Q_{a,max} = 2(k_0d) \), while the maximum attainable scattering efficiency is \( 4Q_{a,max} \). In particular, for both polarizations, the maximum absorption condition is approximately satisfied at one point across the spectrum. This is the well-known conjugate matched condition with \( Q_a = Q_s = Q_{a,max} \). The spectrum also features rapid variations in total scattering and absorption suitable for sensing applications. More details on the specific features of each spectral region will be discussed during the talk.

Acknowledgements

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Spin dynamics in thin films and nanostructures based on Fe\textsubscript{60}Al\textsubscript{40}

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Abstract

We report on ferromagnetic resonance (FMR) detected spin pumping in Fe\textsubscript{60}Al\textsubscript{40}/Pd and Fe\textsubscript{60}Al\textsubscript{40}/permalloy bilayers, and laterally patterned Fe\textsubscript{60}Al\textsubscript{40} nanostructures with periodical ferromagnetic/paramagnetic interfaces. Due to its magnetostructural phase transition Fe\textsubscript{60}Al\textsubscript{40} can be utilized as a paramagnetic or ferromagnetic material at the same temperature depending on its structural order parameter. In this study we investigate the dual role of this alloy as a spin source and a spin sink.

1. Introduction

Spin pumping is a transfer of angular momentum from a ferromagnetic layer to adjacent paramagnetic or diamagnetic layer via microwave excitation and ferromagnetic resonance. Here, we utilize magnetostructural phase transition in 3d metal binary alloy Fe\textsubscript{60}Al\textsubscript{40} which magnetic properties can be tuned via the change of an order parameter \([1-4]\) and investigate the dual role of thin Fe\textsubscript{60}Al\textsubscript{40} film as a spin source and a spin sink in spin pumping experiments. Structural disorder can be achieved during the deposition of thin films at room temperature, alternatively, annealed B2-ordered paramagnetic FeAl can be “switched” to ferromagnetic state using ion irradiation.

2. Experimental methods

The polycrystalline films of Fe\textsubscript{60}Al\textsubscript{40} permalloy Ni\textsubscript{80}Fe\textsubscript{20} (Py) and Pd were grown using magnetron sputtering. The temperature treatment of Fe\textsubscript{60}Al\textsubscript{40} thin film allows for control of structural order and magnetic state – films deposited at room temperature have a chemically disordered A2 structural phase which is ferromagnetic, while post-annealing at \(500^\circ\text{C}\) for \(1\text{ h}\) \textit{in situ} leads to non-ferromagnetic B2 structural phase. Paramagnetic and ferromagnetic Fe\textsubscript{60}Al\textsubscript{40} films have been capped with permalloy Py and Pd thin films, correspondingly. Thus, two series of bilayer samples with varied thickness of paramagnetic film have been studied. Laterally patterned magnetic landscapes representing a periodical ferromagnetic stripes pattern of 500 nm width separated by paramagnetic stripes of 100-400 nm width have been created using Ne ion beam irradiation of B2-ordered Fe\textsubscript{60}Al\textsubscript{40} film covered with lithographically prepared mask (Fig. 1).

![Figure 1: Ion irradiation with Ne\textsuperscript{+} of the Fe\textsubscript{60}Al\textsubscript{40} film with a mask. The structural disordering occurs in the regions which are not protected with the mask, causing the transition from paramagnetic to ferromagnetic state.](image)

3. Results

The frequency-dependent FMR linewidth was determined for out-of-plane applied magnetic field and analyzed for varied thickness of paramagnetic layers. We used the reference measurements of single ferromagnetic layers (without adjacent spin-sink layers) to separate contributions of the intrinsic Gilbert damping and the spin-pumping and evaluate a spin-mixing conductance and a spin diffusion length. From the series of ferromagnetic Fe\textsubscript{60}Al\textsubscript{40}/Pd bilayers the spin diffusion of Pd was determined as \(\lambda_{\text{Pd}} = 8.5\pm1.6\text{ nm}\) which is close to the values available in literature. From the series of paramagnetic Fe\textsubscript{60}Al\textsubscript{40}/Py samples the spin diffusion length of B2-ordered Fe\textsubscript{60}Al\textsubscript{40} was obtained.

For the case of laterally patterned Fe\textsubscript{60}Al\textsubscript{40} samples representing a periodical array of ferromagnetic and paramagnetic stripes, we observed the decrease of damping with the decreasing width of paramagnetic stripes. We relate this to the fact that spin pumping is an interfacial phenomenon, and therefore depends on the configuration of interfaces, namely on their amount per volume of the sample.
4. Conclusions

Performing ferromagnetic resonance study, we have analyzed the spin pumping efficiency of Fe$_{60}$Al$_{40}$ alloy in bilayer systems acting as spin sink and as spin source. Based on the series of bilayers Fe$_{60}$Al$_{40}$/Py we determine the spin diffusion length of paramagnetic B2-ordered Fe$_{60}$Al$_{40}$ as $\lambda_{FeAl} = 11.8 \pm 0.4$ nm. We show a linear increase of magnetic damping in laterally patterned Fe$_{60}$Al$_{40}$ nanostructures with an increase of amount of interfaces between the para- and ferromagnetic regions.

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References


Hexagonal boron nitride for integrated quantum photonics

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Abstract

Integrated quantum photonic circuitry is an emerging topic that requires efficient coupling of quantum light sources to waveguides and optical resonators. So far, great effort is devoted to engineering on-chip systems from 3D crystals such as diamond or gallium arsenide. In this work, room-temperature coupling is demonstrated of quantum emitters embedded in layered hexagonal boron nitride to an on-chip photonic waveguides and cavities. The results serve as foundation for integrating layered materials to on-chip components and realizing integrated quantum photonic circuitry.

1. Introduction

Implementation of quantum technologies, such as quantum networks and photonic processors, require interfacing multiple single photons on a chip. For this purpose, efficient integration between quantum light sources and photonic devices, such as waveguides and cavities, is essential. A new emerging approach is the use of single photon emitters in 2D materials [1]. 2D materials can be transferred onto any photonic structures via exfoliation and stamping, which typically is a challenging task for bulk materials due to lattice constant mismatch.

Hexagonal boron nitride (hBN), a 2D crystalline sheet consisting of alternating boron and nitrogen atoms, is emerging as a promising candidate for integrated quantum photonics due to its bright single photon emission at room temperature [2]. These emitters benefit from weak electron-phonon coupling indicated by the high intensity of zero phonon lines (ZPL) and weak intensity in the phonon sideband. Here, we present the hBN quantum emitters integrated into photonic waveguides and photonic cavities.

2. Results and discussion

2.1. Waveguide integration

In this work, we report the integration of room-temperature hBN single photon emitters with aluminium nitride (AlN) waveguides [3]. The refractive index of AlN (n=2.08) is close to that of hBN (n=2.1) [4], which minimize the coupling loss due to minimized light reflection at the AlN/hBN interface.

The optical excitation laser used for this experiment is a continuous-wave, 532 nm laser. In the conventional photoluminescence (PL) map, the excitation and the collection are from the same spot as the sample is scanned using either piezo stage or a scanning mirror, and we refer to this scheme as local excitation-collection. The emitter in this experiment was analyzed using a modified collection technique, which we refer to as nonlocal excitation-collection. The confocal map for the nonlocal scheme is shown in Fig. 1a. The image reveals luminescence both from the emitter (point A) and the coupler (point B). This demonstrates successful coupling and propagation of single photons from the hBN emitter through the waveguide. The emission collected at point B is further analyzed with a...
spectrometer and Hanbury-Brown Twiss (HBT) setup and plotted in Fig. 1b. In the next step, the device was tested in what we refer to as reverse collection, i.e., with the excitation spot fixed at the grating coupler and the collection scanned across the sample. The PL map and the spectrum (g^{(2)} correlation in the inset) are shown in Fig. 1c and 1(d), respectively. We achieved a coupling efficiency of 1.35% for the hybrid system, which matches—upon considering system nonidealities—the theoretical limit of ≈7.75% is estimated for the structure using finite-difference time-domain (FDTD) simulations.

2.2. Cavity integration

We report the on-chip integration of hBN quantum emitters with one-dimensional photonic crystal nanobeam cavities fabricated from silicon nitride (Si₃N₄) [5]. We observed quantum emitters at the center of the photonic crystal cavity, as shown in Fig. 2a, whose ZPL overlapped with a cavity resonance. Fig. 2b shows an example of a spectrally jumping quantum emitter and a fixed cavity resonance. The ZPL of a quantum emitter was initially identified at 598 nm, close to the cavity mode at 593 nm. During the course of the PL measurement, a first shift of the ZPL occurred, which resulted in an overlap of the ZPL and the main cavity mode. Consequently, a second shift of the ZPL detuned the emitter from the cavity mode, followed by photobleaching of the emitter. The intensity at the ZPL increased from 1.9 to 9.3 after the first shift and decreased to 1.5 after the second shift.

Figure 2. Coupling hBN quantum emitters to photonic crystal cavities. (a) A PL map showing the emitter is located at the center of the cavity. (b) Dynamic enhancement of a quantum emitter which spectrally diffused to a cavity mode.

3. Conclusions

We demonstrate on-chip integration of hBN single photon emitters with AlN waveguide and SiN photonic crystal cavities. Our results outline a promising route toward scalable on-chip quantum photonic networks that harness the properties of quantum emitters in hBN as quantum light sources.
Resonant Heat Transfer in Nanophotonics Driven Thermal Water Desalination

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Abstract
Light absorbing nanoparticles can efficiently convert electromagnetic radiation into heat in nanoscale regions. This photothermal effect can be exploited to locally increase the temperature of water, promoting its evaporation and thus purification. Optothermal nonlinearities and resonant thermal phenomena have been uncovered to improve the efficiency of this process. Here we show how these concepts together can be engineered to achieve fresh water production rates up to ~20 L/(m²·day) under standard solar irradiation.

1. Introduction
Light absorbing nanostructures can couple to electromagnetic radiation and generate heat in nanoscale regions. Recent research [1,2] has demonstrated that broadband light absorbing nanoparticles dispersed in water enhance evaporation rate, providing a method to generate steam and purify water, using sunlight. Many existing water purification technologies require costly infrastructures and rely on electricity or fossil fuels to operate. Recently, we have introduced the concept of nanophotonics-enabled solar membrane distillation (NESMD), in which solar-driven localized heat drives the distillation process [3]. NESMD is a low-cost Sun-powered scalable water desalination system, which can be deployed in regions lacking access to drinking water and/or electric power supply. In the effort to increase light-to-fresh water conversion efficiency, it will be shown how the use of small optical elements and energy recovery strategies have the potential to push daily water purification rates up to ~20 L for 1 m² device footprint.

2. Discussion
NESMD is based on the concept of membrane distillation (MD), where two countercurrent fluids are separated by a hydrophobic membrane (PVDF) which let water vapor to diffuse, while blocking liquid transport. NESMD modifies MD through the deposition of a highly absorptive layer (~5-10 μm) of carbon black (CB) nanoparticles (NPs) between the saline input feed and the membrane. See Fig. 1a.

Figure 1: a) Scheme of NESMD: two countercurrent water flows are separated by a hydrophobic PVDF membrane. A micron size layer of carbon black nanoparticles are placed between the membrane and the input saline water and are irradiated by sunlight. The vapor pressure difference pushes water vapor across the membrane and it is collected as fresh water. b) Same as a) with optical lenses covering the surface of the NESMD device, generating thermal hot spot at the membrane surface. c) Fresh water flux rate (right axis)
generated during a typical sunny day with varying input irradiation (dashed, blue line, left axis) with (orange area) and without lenses (gray area). Orange and gray dots represent experimental data. Adapted from [3,4].

Recently we have coupled the NESMD device with a heat exchanger (HX) with the aim of recovering condensation heat, recycling it to drive further vaporization (see fig. 2a). [5]. Despite the simplicity of the concept, we have found that the whole system can be described as a thermal resonator, offering the possibility to exploit properties typical of oscillatory systems. Several HX layers can be also stacked to recover heat more effectively. In Fig. 2b, we show how the use of n=10 HX layers can yield to more than ~20 L/(m²·day) when an optimal heat recovery strategy is implemented (orange area). Optimal heat recovery can be achieved by real time tuning of the input feed and distillate flow rates, depending on system losses and input irradiation (which varies during the day). Heat recovery alone, without flow rates control yields to a sensitively lower production rate (light gray area). The absence of heat recovery provides even less fresh water (dark gray area), even with real time flow control (red area). See Fig. 2b.

3. Conclusions

We have shown how light absorbing carbon black nanoparticles can be utilized in a membrane desalination device to generate fresh water using sunlight as input power source. The concept of Nanophotonics Enables Solar Membrane Distillation (NESMD) has been theoretically understood and experimentally demonstrated. In the last few years the yield of the process has been increased by almost ten times, from ~2 to ~20 L/(m²·day), showing the potential for this technology to provide water off-grid for families or small community use.

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Light amplification by silver nanoparticles surface plasmon resonance

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Abstract
Organic materials have several advantages in the fields of an organic light-emitting diode (OLED) and organic photovoltaics (OPV), but in the same time they have lower stability and efficiency in comparison to inorganic compounds. It can be improved by introducing metallic nanoparticles into the organic media. In this work we study silver nanoparticles synthesis in aqueous solution, their transfer to organic solutions, their impact on organic luminescent material emission and photoluminescence parameters – quantum yield, radiative and non-radiative decay rate, luminescence lifetime.

1. Introduction
Photoluminescence (PL) process found its application in variety of field like LED, photovoltaics [1], biosensing, imaging, medicine [2] etc. Luminophores with high quantum yield (QY) are in particular interest for practical approach, but the most of organic luminescent materials have low QY what is not so useful for applications. However, QY of organic compounds can be significantly increased by introducing metallic nanoparticles (NPs) into organic media. Collective electron oscillations on the surface of metallic nanoparticle (NP) enhance light-mater interaction and emission from luminophore can be increased. There are many aspects should be taken into an account – there is no one universal rule for optimal distance between luminophore and NP [3][4][5][6][7], thus required NPs concentration should be tested; high concentration of NPs can quench emission; nanoparticles of appropriate forms and absorption spectra should be used. If NPs absorption spectrum does not correlate with luminophore absorption, no enhancement can be achieved.

In this work we studied NPs effect on organic luminophore DWK-1-TB PL parameters – QY, lifetime, radiative and non-radiative decay rate. We showed that NPs can enhance emission and QY at NPs absorption spectrum, thus it broadens luminophore excitation spectra, avoiding high absorption problem, when light penetration depth in luminophore at maximal absorption wavelength \( \lambda = 480 \) nm is very low in comparison to NPs high absorption wavelength \( \lambda = 375 \) nm, which emission is tuned to luminophore maximal absorbance. Luminophore can be excited at wavelength with high material penetration depth allowing more luminophore molecules interact to light, what improve PL parameters.

2. Experimental
2.1. Materials
AgNO3 (\( \geq 99.8\% \), Supelco), deionized water, dichloromethane (DCM, \( \geq 99.8\% \), Sigma-Aldrich), 2-Aminoethanethiol (99.9%, Flourochem), oleic acid (OA, 99%, Alfa Aesar), Hydroxylamine hydrochloride (99+%, ACROS Organics™), methanol (\( \geq 99.9\% \)), luminophore DWK-1-TB (synthesized at Riga Technical University [8]). All the reagents and solvents were used as received without any further purification.

2.2. Preparation of luminophore solution containing silver nanoparticles.
Solutions of core-shell silver NPs were prepared adding 100 mmol of sodium borohydride into a 90 ml deionized water solution containing 0.2 mmol of silver nitrate and 0.5 mmol of sodium citrate. The silver solution was allowed to react at 60 °C while being stirred. Observing a dark yellow color indicated spherical NPs formation [10]. Ag NPs structure was studied with TEM FEI TECNAI (Figure 1).

![Prepared NPs image obtained with TEM](image-url)

Figure 1: Prepared NPs image obtained with TEM

Sodium citrate captured silver NPs were transferred to organic solvent DCM by shell changing method. Thiol-termination ligand was synthesized in methanol using 2-Aminoethanethiol, oleic acid, hydroxylamine hydrochloride
Silver NPs in DCM of different concentrations were added to organic luminophore DWK-1-TB solution. Structure of DWK-1-TB can be seen on Figure 2. DWK-1-TB concentration in all solutions containing NPs were c = 1 mmol/l. Emission, lifetime, PL QY of prepared solutions were measured with Edinburgh Instruments FLS1000 photoluminescence spectrometer. Absorption spectra were measured with Agilent spectrophotometer Cary 7000.

3. Results and discussion

Nanoparticles transfer from aqueous to organic media is accompanied by the changes in absorption and concentration. Transfer rate is not absolute and some NPs can be left in aqueous solution. In absorption spectra of pure NPs solutions in water and DCM (Figure 3) shifting in the absorption peak of NPs solution [11], and changing of absorption peak FWHM [12] can be observed, caused by shell changing and decrement of dielectric constant of surrounding media. Shell of nanoparticle has hydrophobic tail from OA allowing dispersion in organic media, but it is responsible for high absorption at near UV region [13]. After mixing luminophore and NPs solution, absorbance of DWK-1-TB - NPs solution increases (Figure 4).

Figure 3: Normalized absorption spectra of synthesized NPs in DCM and aqueous solution

To study nanoparticles concentration dependence on luminophore PL properties, solutions with equal luminophore DWK-1-TB and different NPs content were prepared. Concentration of NPs in the solution was estimated in relative units. A solution had 0 unit of NPs, B – 1 unit of NPs, C solution – 5 units of NPs, D solution – 9 units of NPs. The results are compiled in Figure 5.

DWK-1-TB solution emission diapason is located in wavelengths λ = 550-650 nm with a peak at wavelength λ = 590 nm. The emission can be excited with wavelengths λ = 440 - 510 nm, but maximal emission is achieved with excitation wavelength λ = 480 nm what correspond to maximal absorbance peak of this solution. Excitation below λ = 440 nm is neglectable. The most intensive emission of NPs in DCM is excited by UV light and located in λ = 350 – 450 nm range. However, there are significant emission in visible region excited by wavelengths λ = 340 - 440 nm. This emission is located in spectral region where DWK-1-TB molecules have lower absorption and no luminophore emission can be excited, nevertheless in DWK-1-TB – NPs system emission at luminophore characteristic wavelength can be observed. Explanation of this process is energy transfer between organic luminophore and NPs. NPs are excited by λ = 350-400 nm and emit light further in blue region, where DWK-1-TB can absorb it and emit light at orange region.

DWK-1-TB has the most intensive emission if excitation light is at wavelengths λ = 460 – 500 nm, NPs don’t emit light at this region, but emission is significantly increased in solution D. Since there are no emission changes between B and C solution, higher index of absorption can’t be an explanation for emission increment. Metallic nanoparticles are well known for their ability to scatter the light [14]; thus in solution D more luminophore molecules are illuminated in the direction perpendicular to light propagation and solution can emit more light.

To make material more effective emission enhancement should be accompanied by QY increment, wherefore NPs contribution to solution radiative efficacy was studied by measuring QY and luminescence lifetime (τ). Knowing
Figure 5 Emission maps of Solution A - DWK-1-TB solution in DCM, B solution - DWK-1-TB solution containing 1 part of NPs, C solution - DWK-1-TB solution containing 5 parts of NPs, D solution - DWK-1-TB solution containing 9 parts of NPs and emission map of NPs solution in DCM without DWK-1-TB.
Table 1 Luminescence parameters of A, B, C and D solutions

<table>
<thead>
<tr>
<th>Solution</th>
<th>NPs conc, r.u</th>
<th>QY_{375nm}, %</th>
<th>τ, ns</th>
<th>Γ_{375nm} \cdot 10^7, s^{-1}</th>
<th>QY_{480nm}, %</th>
<th>Γ_{480nm} \cdot 10^7, s^{-1}</th>
<th>\kappa_{non} \cdot 10^8, s^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>10.82</td>
<td>1.24</td>
<td>8.73</td>
<td>22.96</td>
<td>1.85</td>
<td>7.20</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>16.96</td>
<td>1.45</td>
<td>11.7</td>
<td>23.68</td>
<td>1.63</td>
<td>5.72</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>10.36</td>
<td>1.65</td>
<td>6.27</td>
<td>17.26</td>
<td>1.05</td>
<td>5.43</td>
</tr>
<tr>
<td>D</td>
<td>9</td>
<td>9.59</td>
<td>1.83</td>
<td>5.24</td>
<td>16.79</td>
<td>0.92</td>
<td>4.94</td>
</tr>
</tbody>
</table>

Table 2: Light penetration depth in B, C and D solutions at wavelength λ = 375 nm

<table>
<thead>
<tr>
<th>Solution</th>
<th>NPs conc, r.u</th>
<th>s, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>0.1</td>
<td>1.47</td>
</tr>
<tr>
<td>C</td>
<td>0.5</td>
<td>0.32</td>
</tr>
<tr>
<td>D</td>
<td>0.9</td>
<td>0.19</td>
</tr>
</tbody>
</table>

4. Conclusion

Photoluminescence parameters of organic luminophore DWK-1-TB solution can be changed by introducing silver core-shell NPs into solution. Interaction between luminophore and NPs strongly depends on NPs concentration in the solution. Emission from NPs containing solution is higher and new wavelengths can excite emission at DWK-1-TB characteristic spectral range, indicating interaction between NPs and luminophore. PL parameters measured at wavelength which is absorbed by both - luminophore and NPs increases in B solution indicating optimal NPs concentration in DWK-1-TB solution, where NPs quenching is not present or enhancement process overcomes it. In solutions with greater NPs concentration enhancement processes present but it is attenuated by NPs quenching and high absorption coefficient. PL parameter measured at wavelength which is mainly absorbed by luminophore has greater decrement and it is product of absorption changes without plasmonic PL enhancement.

Acknowledgements

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References


High performance infrared magnetoplasmonics with transparent conductive oxide nanostructures

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Abstract

Magnetoplasmonics, the combination of magnetic fields and light polarization to actively and remotely modulate the plasmonic response of nanostructures triggered significant improvements in optical nanodevices for telecommunications and refractometric sensing. Two main factors guide the design of high performance magnetoplasmonic platforms: a strong modulation of the plasmonic response and a sharp plasmon resonance. Within this framework, noble metal nanocrystals [1], nickel ferromagnetic nanodisks [2] or hybrid bimetallic nanostructures [3] have been proposed. While noble metals offer relatively sharp resonances, their weak magnetic response limits applicability. On the other hand, hybrid or ferromagnetic magnetoplasmonic nanostructures offer strong field response, at the cost of severely broadened resonances.

To overcome these issues, we propose a paradigm shift in material choice, shifting the attention to a novel class of plasmonic materials: transparent conductive oxides. Here we show that colloidal dispersions of tin-doped indium oxide (ITO) nanoparticles, with a sharp plasmon resonance in the near infrared, afford a 20-fold enhanced magnetic modulation with respect to Au, as detected by magneto-optical spectroscopies. We ascribe the enhanced magneto-optical response to the reduced free electron effective mass (m*) of free carriers in ITO with respect to most metals, which in turn boosts the magnetic modulation. The latter is given in first approximation by the cyclotron frequency ωC, which is inversely proportional to m* and directly proportional to the applied field [1,4]. A further enhancement of the magneto-optical response was achieved in F- and In-co-doped cadmium oxide (FICO) nanoparticles, which display a 2-fold reduced plasmonic line width with respect to ITO and comparable effective mass [5,6].

Finally, using FICO NCs in a proof-of-concept magnetoplasmonic refractometric sensing experiment we obtained a superior refractive index sensitivity with respect to the most promising magnetoplasmonic systems reported in the literature [1-3] and performance competitive with the current state of the art of plasmonic refractometric sensing employing extinction spectroscopy [7], with the advantage of not requiring complicate curve fitting.

FIGURES

Figure 1: Proof of concept of a magnetoplasmonic refractometric sensing experiment. Change in magneto-optical ellipticity of ITO (left) and FICO (right) nanoparticles in media with different refractive indexes.
REFERENCES

Metasurfaces and 2D Metamaterials in microwave region
Angular Scattering Control with Multilayer Metasurface Stacks

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Abstract
In order to implement metasurface-based optical analog processing systems, we develop an analysis technique for computing the angular scattering response of multilayer metasurface stacks. This technique is based on an improved scattering matrix method and applies to bianisotropic metasurfaces for optimal field control.

1. Introduction
Being able to engineer the angular scattering response of a metasurface is essential for the implementation of metasurface-based optical analog processing systems [1,2]. For this purpose, we have investigated the angular scattering properties of metasurfaces in [3], and now show how they can be controlled using single or multilayer stacks of metasurfaces. To do so, we develop a mathematical and numerical analysis technique by combining together the zero-thickness metasurface model based on the generalized sheet transition conditions (GSTCs) derived in [4–8], with the improved scattering matrix method proposed in [9], which is particularly well-suited for the scattering analysis of multi-layer metasurface stacks. The resulting technique applies to the general case of bianisotropic metasurfaces and also takes into account the excitation of polarizations normal to the metasurface plane, which provides additional degrees of freedom for achieving advanced angular scattering control [3].

2. Metasurface Angular Scattering
A uniform metasurface lying in the xy-plane at z = 0 may be modeled using the GSTCs as [4–8]

\[ \hat{z} \times \Delta H = j\omega \mu_{\text{av}} \cdot E_{\text{av}} + jk\mu_{\text{mm}} \cdot H_{\text{av}}, \]  
\[ \hat{z} \times \Delta E = -j\omega \varepsilon_{\text{av}} \cdot H_{\text{av}} + jk\varepsilon_{\text{mm}} \cdot E_{\text{av}}, \]  

where \( \Delta E, \Delta H, E_{\text{av}}, \) and \( H_{\text{av}} \) are the differences and averages of the fields, respectively, and \( \varepsilon_{\text{av}}, \mu_{\text{av}}, \mu_{\text{mm}}, \varepsilon_{\text{mm}} \) and \( \mu_{\text{me}}, \varepsilon_{\text{me}} \) are the metasurface electric, magnetic and magneto-electric susceptibility tensors, respectively.

The angular scattering response of a given metasurface may then be obtained by defining the fields in (1) as those of an obliquely propagating plane wave being reflected and transmitted with coefficients \( R \) and \( T \), respectively. The differences of the fields in (1), assuming TM polarization for simplicity, are thus expressed as

\[ \Delta E = \pm \frac{k_z}{k} (1 + R - T), \quad \Delta H = \frac{1}{\eta_0} (-1 + R + T), \]  

where the top sign in \( \Delta E \) corresponds to an incident wave propagating the backward z-direction, while the bottom sign corresponds to propagation in the forward z-direction. Similarly, the averages of the fields are given by

\[ E_{x,\text{av}} = \frac{k_z}{2k} (1 + T + R), \quad E_{z,\text{av}} = \frac{k_z}{2k} (1 + T - R), \]  
\[ H_{y,\text{av}} = \mp \frac{1}{2\eta_0} (1 + T - R). \]  

The metasurface angular response may now be found by substituting (2) and (3) into (1) and solving the resulting system for \( R \) and \( T \) [3]. The corresponding expressions for \( R \) and \( T \) are provided in Eq. (4) below.

3. Transfer-Matrix Method
In order to achieve a desired angular scattering response, either in reflection or in transmission, one should optimize the value of the susceptibilities in (4), which ultimately correspond to the shape of the scattering particles composing the metasurface. However, since these equations only apply to a single metasurface, the resulting number of degrees of freedom is inherently limited. One way of overcoming this limitation is to stack several metasurfaces one after the other, each separated by a dielectric spacer. This drastically increases the number of available degrees of freedom, thus allowing advanced angular scattering control.

To analyze the scattering from a stack of metasurfaces, we use the scattering matrix method developed in [9] and whose working principle is illustrated in Fig. 1. In this formulation, a scattering matrix is associated to each element of the stack assuming that it is surrounded, on both sides, by a zero-thickness layer of vacuum. This assumption is particularly convenient since it allows us to directly use Eqs. (4) as they were derived for a metasurface in vacuum. Finally, the angular scattering response of the multi-layer metasurface stack is obtained by expressing the global scattering matrix as follows

\[ S^{(\text{global})} = S^{(\text{ref})} \otimes \left[ S^{(1)} \otimes S^{(2)} \otimes \cdots \otimes S^{(N)} \right] \otimes S^{(\text{tm})}, \]  

where

\[ S^{(i)} = \begin{bmatrix} R_i & T_i \\ T_i & R_i \end{bmatrix}, \]

and

\[ S^{(\text{ref})} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \]
\[ R = \frac{2}{C_b} \left\{ k_2^2 \chi_{ee}^{xx} - k_2^2 \chi_{ee}^{xx} - k_2 [k_2 (\chi_{ee}^{xx} - \chi_{ee}^{xx}) \pm k(\chi_{em}^{yy} - \chi_{me}^{yy})] \mp kk_2 (\chi_{em}^{yy} + \chi_{me}^{yy}) + k^2 \chi_{mm}^{yy} \right\}. \]  
\[ T = \frac{jk_2}{C_b} \left\{ k_2^2 [\chi_{ee}^{xx} \chi_{ee}^{xx} - \chi_{ee}^{xx} \chi_{ee}^{xx}] + (2j \mp k \chi_{em}^{yy}) (2j \mp k \chi_{me}^{yy}) \right\} \]
\[ + k_2 [\chi_{ee}^{xx} (2j \pm k \chi_{em}^{yy}) + \chi_{ee}^{xx} (2j \mp k \chi_{me}^{yy})] \pm k_2 [\chi_{ee}^{xx} (\chi_{em}^{yy} + \chi_{me}^{yy}) - k^2 \chi_{ee}^{yy} \chi_{mm}^{yy}]. \]
\[ C_b = 2 \left[ k_2^2 \chi_{ee}^{xx} + jk_2 k_1 \chi_{em}^{yy} \chi_{mme}^{yy} + k_2 \chi_{em}^{yy} \chi_{mme}^{yy} + k^2 \chi_{mm}^{yy} \right] \pm k_2 [\chi_{ee}^{xx} \chi_{ee}^{xx}] \mp kk_2 [\chi_{ee}^{xx} \chi_{em}^{yy} \chi_{me}^{yy} - \chi_{ee}^{xx} (\chi_{em}^{yy} + \chi_{me}^{yy})]. \]

\[ S^{(a)} \quad S^{(1)} \quad S^{(2)} \quad S^{(3)} \quad S^{(4)} \quad S^{(5)} \quad S^{(6)} \]
Incident medium
MS_1
L_1
MS_2
L_2
MS_3
Transmission medium

Figure 1: Multilayer metasurface stack with zero-thickness gaps in-between each layer.

where \( \odot \) represent the Redheffer product \([9]\). Examples illustrating the application of this technique are shown in Fig. 2, where a stack of 2 metasurfaces have been used.

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**References**


Glide-Symmetric Luneburg Lens Based on Substrate-Integrated-Holes

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Abstract

We propose a novel parallel plate waveguide (PPW) meta-surface. The PPW is periodically loaded with glide-symmetrically arranged dielectric-filled cavities in both conductors. By filling the cavities with dielectric, the equivalent refractive index increases. To facilitate the manufacturing using conventional methods, the walls of the cavities are implemented with metallic vias and the proposed structure is used to design a Luneburg lens. Compared to previous works on holey metasurfaces, the designed lens is cheaper and more resilient to manufacturing errors.

1. Introduction

Millimeter-wave (mm-wave) frequencies are intended to be used to meet the increasing requirements on the data rates in future cellular communication networks (5G and beyond). Wave propagation at these frequencies are subject to higher free-space path-loss (FSPL), compared to the traditionally used sub-6 GHz frequencies. In order to mitigate the effect of the higher FSPL, high-gain antennas are employed. The high gain results in a narrow beamwidth, and therefore, beam steering is required in these antenna systems.

Traditionally, array antennas are used to produce steerable directive beams. However, for mm-waves, the feeding network of arrays is expensive and introduces losses. Alternatively, lens antennas can be employed [1]. The beam steering in these antennas is often done mechanically or through electrical switching, which results in a reduced cost for the system.

One lens solution that is attractive for beam-steering applications is the Luneburg lens. The Luneburg lens is a gradient index lens that transforms a spherical wave at a point on its surface to a plane wave at the diametrically opposite side. The refractive index distribution is rotationally symmetric and consequently, the beam can be steered by moving the feed point mechanically along the surface of the lens or by electronically switching between multiple feed elements.

The Luneburg gradient index distribution can be implemented in different ways. For instance, in [2], a spherical dielectric Luneburg lens is realized by discretizing the refractive index distribution in layers. It is demonstrated that the equivalent refractive index of such structures is increased when the cavities are filled with a dielectric. The unit cell of the structure studied in [8] is illustrated to the left in Fig. 1. To facilitate the manufacturing using conventional techniques, the lateral walls of the cavities are in this work approximated with metallic vias, as illustrated to the right in Fig. 1.

To reduce the size and cost of the antenna system, a two-dimensional (2D) Luneburg lens can be employed. The refractive index distribution can be realized with a meta-surface in a parallel plate waveguide (PPW) [3]. Recently, due to the advances in glide-symmetric metasurfaces, 2D Luneburg lenses operating in the Ka-band have been designed in fully metallic [4; 5] or hybrid metallic-dielectric structures [6]. These designs provide a wide bandwidth and low losses. However, they are expensive to manufacture and/or sensitive to manufacturing tolerances, mainly due to the narrow PPW gap required.

In this work, we propose a novel glide-symmetric structure that allows for a larger PPW gap and which can be cost-effectively manufactured using printed circuit board (PCB) technology. We call this structure substrate-integrated-holes (SIHs) [7]. Additionally, a Luneburg lens is designed using the proposed structure.

2. Glide-Symmetric SIHs

We analyze parallel plate waveguides periodically loaded with cavities in both conductors. The cavities in the two conductors are identical but off-shifted with respect to each other by half a period (glide symmetry). In [8] and [9], it was demonstrated that the equivalent refractive index of such structures is increased when the cavities are filled with a dielectric. The unit cell of the structure studied in [8] is illustrated to the left in Fig. 1. To facilitate the manufacturing using conventional techniques, the lateral walls of the cavities are in this work approximated with metallic vias, as illustrated to the right in Fig. 1.

The proposed unit cell is simulated using the Eigenmode solver of CST Microwave Studio. The equivalent refractive index can be tuned by varying the hole size, $s$, as illustrated in Fig. 2. The other dimensions are: $p = 3.2$ mm, $g = 0.6$ mm, $h = 1.524$ mm, $d_{\text{via}} = 0.53$ mm, $d_{\text{via}} = 0.3$ mm, and $\varepsilon_r = 3$. 

Figure 1: Unit cell of the proposed structure.
The proposed structure provides almost identical achievable range of equivalent refractive indices and level dispersion as the reference works [5; 6]. However, the employed PPW gap is significantly larger (two and six times compared to [5] and [6]).

3. Luneburg Lens Design

The refractive index distribution of the Luneburg lens [10] is given by

\[ n(\rho) = n_0 \sqrt{2 - \frac{\rho^2}{R^2}} \]  

where \( n_0 \) is the refractive index of the surrounding medium, \( \rho \) is the radial position in the lens, and \( R \) is the radius of the lens. A lens is designed using the proposed structure by spatially varying the hole size throughout the lens. The electric field distribution in the lens is illustrated in Fig. 3. The lens outline is highlighted with a black circle. The cylindrical wave at the focal point is transformed to a planar wave at the other side of the lens. Compared to the reference designs [5; 6], the manufacturing can be cost-effectively done using standard printed circuit board technology (PCB).

4. Conclusions

In this work, a novel PPW metasurface is proposed. The unit cell of the metasurface consists of dielectric-filled cavities in both conductors of the PPW and the cavities in the two conductors are glide-symmetrically arranged. Compared to the previously studied PPW holey metasurfaces, the proposed structure is less expensive and more resilient to manufacturing errors. To highlight the advantages of the proposed structure a Luneburg lens is designed and compared to the previously reported designs. Similar performance is obtained (range of achievable refractive indices and level of dispersion) with a PPW gap that is two [5] and six [6] times larger. Furthermore, the implementation of the lens is readily manufactured using standard PCB technology. The proposed structure can be used to design quasi-optical beamformers for future cellular communication networks (5G and beyond).

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Reference

Independent Manipulation of Orthogonal Circular Polarizations based on Microwave Metasurface

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Abstract

In this paper, a transmissive-type metasurfaces based on multi-layer structure is proposed to independently manipulate the orthogonal circularly polarized wave in microwave region. Through combining the propagation phase and geometry phase principles, the opposite circularly polarized transmitted wave can be imposed independent spatial phase distributions to perform different wavefronts. Experimental measurement are conducted and effectively verified the feasibility of the proposed theory for artificial manipulation of circular polarization manipulation in microwave region.

1. Introduction

Polarization is one of the intrinsic attributes of planar electromagnetic (EM) wave [1]. Traditional methods of polarization manipulation are birefringence [2], photonic crystals [3], metasurfaces [4] and so on. The geometric phase also known as Pancharatnam-Berry phase can be employed to convert the left-right-handed circular polarized (LHCP/RHCP) incident wave into its opposite circular handedness with totally symmetrical characteristics [5]. However, the inherent restrictions of this symmetry characteristic have limited the applications in wireless systems [6]. Various works have been proposed to figure out the symmetry limitation in orthogonal polarization manipulation of EM wave [7].

In this paper, transmissive multi-layer metasurface is proposed to realize polarization-independent output wavefronts at microwave frequencies. The simulation and measurement results demonstrate that the desired polarization-independent wavefronts can be achieved in a wide frequency band, suggesting promising applications in wireless communication systems.

2. Principles and results

The schematic of polarization-independent refraction is shown in Fig. 1. Under the orthogonal circularly polarized incident waves, the transmitted wave can be refracted into different and independent directions by elaborately designed metasurface.

Figure 1: Schematic of proposed metasurface for generating polarization-independent vortex beam and converging beam.
Figure 2: (a) The schematic of proposed multi-layer unit cell (b) The corresponding equivalent circuit model of unit cell.

Figure 3: Simulated and measured energy and phase distributions of cross-polarized converged wave under RHCP incident wave.

In order to verify the performances of the designed meta-deflectors, full-wave simulations based on the finite difference time-domain technique (FDTD) are conducted at 10 GHz. The simulation results of metasurface for independent manipulation of CP waves are shown in Fig. 3 and Fig. 4. It can be observed that under LHCP incident wave, the transmitted wave are exhibited as vortex beam carrying orbital angular momentum (OAM) with mode $l = 2$, which are in accordance with the theoretical design. The corresponding simulated and measured results are shown in Fig. 3. Fig. 4 presents the simulated and measured converged beam in cross-polarized transmitted field under LHCP incidence. It can be clearly observed that the transmitted energy has been effectively converged into the preset point with the desired focal length. Through comparing the energy distributions in Fig. 3 and Fig. 4, distinct wavefronts are performed in corresponding cross-polarized fields under the illuminations carrying opposite CPs, indicating that the proposed scheme can effectively achieve independent manipulation for CP waves.

Figure 4: Simulated and measured energy and phase distributions of cross-polarized vortex beam under LHCP incident wave.

3. Conclusions

To summarize, a general scheme to design multi-layer metasurface for polarization-independent manipulation of EM wave is presented in this paper. The simulated and measured results verify the designed metasurface has ability to perform transmitted waves with required functionalities. The design method proposed in this paper shows great potential to meet various requirements of microwave wireless communication systems.

References

Anisotropic Electromagnetic Wave Propagation in Two Dimensional Ferromagnetic Metamaterials

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Abstract
It is well known that metamaterials are artificial structures providing electromagnetic properties that natural materials do not have. There is a class of metamaterials called ferromagnetic metamaterials possessing a negative permeability in microwave range and a permittivity that can change its sign in terahertz range [1]. In this paper, both the anisotropic properties and dispersion characteristics of fast and slow electromagnetic waves (EMWs) propagating in two-dimensional ferromagnetic metamaterials (metasurfaces) with finite wire conductivity are studied.

1. Introduction
The two-dimensional ferromagnetic metamaterial is shown in Fig. 1. It is a tangentially magnetized ferromagnetic layer with a periodic structure composed of thin metallic wires. A period of the structure $L$ is supposed to be much smaller than the wavelength of the EMWs ($L << \lambda$). Then dielectric properties of the metasurface can be described by the effective permittivity [3]:

$$\varepsilon_{\text{eff}} = \varepsilon_{\text{fer}} \left(1 + \frac{\omega_p^2}{\omega_\phi^2 \xi^2}\right),$$

where $\varepsilon_{\text{fer}}$ is a ferromagnet permittivity, $\omega_p$ is a plasma frequency, $\xi$ is a damping parameter,

$$\omega_p = \frac{c}{L} \sqrt{\frac{2\pi}{\ln\left(\frac{L}{a}\right)}}; \quad \xi = \frac{2 \omega_\phi^2 \varepsilon_0}{\sigma} \left(\frac{L}{a}\right)^2,$$

$a$ is a wire radius, $c$ is a light velocity in free space, $\sigma$ is a wire conductivity, $\varepsilon_0$ is an electric constant.

The dispersion characteristics of EMWs propagating in the tangentially magnetized ferromagnetic metasurface can be studied on the basis of the dispersion equation obtained for tangentially magnetized ferromagnet [1, 3] combined with the effective permittivity in a view of (1):

$$-\mu k_y^2 - \left\{[\mu(1 + \sin^2 \varphi) + \cos^2 \varphi]k_z^2 - (\mu^2 + \mu - \mu_0^2)k_\phi^2 \varepsilon_{\text{eff}}\right\}k_z^2 = (\mu_0 \sin^2 \varphi + \cos^2 \varphi)k_\phi^4 - [\mu(1 + \cos^2 \varphi) + (\mu_0^2 - \mu^2) \sin^2 \varphi]k_\phi^2 k_\phi^2 \varepsilon_{\text{eff}} + \mu_0^2 k_\phi^4 \varepsilon_{\text{eff}}^2,$$

where $\mu = \omega_M/(\omega_M^2 - \omega^2)$ is a diagonal component of the permeability tensor, $\mu_0 = \omega_M/(\omega_M^2 - \omega^2)$ is a non-diagonal component, $\omega_M$ is a ferromagnetic resonance frequency, $H_0$ is an external static magnetic field, $\omega_M = 4\pi M_0$ is a gyromagnetic ratio, $4\pi M_0$ is a saturation magnetization, $k_0 = \omega/c$ is a wave number in free space, $k$ is a longitudinal wave number in the ferromagnetic metamaterial, $k_y = n \pi d$ is a transverse wave number when the ferromagnetic metamaterial is loaded by the metallic surfaces, $d$ is a metamaterial thickness, $n$ is a volume mode number, $\varphi$ is an angle between a wavevector and the static magnetic field vector.

Figure 1. Two-dimensional ferromagnetic metamaterial

2. Discussion
In Fig. 2, there are the dispersion characteristics of the EMWs propagating in the ferromagnetic metamaterial at different wire conductivity values and wavevector angle values. It is shown, that for ferromagnetic metamaterial with $\varphi \neq 0$ there are four EMWs. Three of them (two fast bulk EMWs and one slow bulk EMW) are peculiar to the ferromagnet, and fourth EMW appears due to the finite wire conductivity. Hereafter it is named as the "conductance wave". Such wave is a slow bulk EMW and its frequency band depends on the wire conductivity value. In the case of metallic wires, the "conductance wave" propagates in microwave range, where the slow backward EMW propagates as well (Fig. 2a). The last one is calculated by the use of the magnetostatic approximation, and therefore it is called a magnetostatic wave. In the case of semiconducting wires, the "conductance wave" shifts to the terahertz range, where two fast EMWs propagate (Fig. 2b). It must be noted that "conductance wave" electromagnetic characteristics...
basically depend on the wire conductivity value, and the external static magnetic field almost doesn’t affect them. If the angle between the magnetic field and the wavevector is changed, a group velocity anisotropy effect is observed for two fast and one slow (magnetostatic) EMWs. This effect is the difference between the group velocity and the wavevector angles.

Figure 2. Dispersion characteristics of (a) slow EMWs propagating in the ferromagnetic metasurface with metallic wires at different angle values ($1-4$ - magnetostatic wave, $1'-4'$ - the “conductance wave”) and (b) fast EMWs ($1, 2$) and the “conductance wave” ($3$) propagating in the ferromagnetic metasurface with semiconducting wires. The following system parameters were used for the calculation: $d = 10$ um, $H_0 = 47.76$ kA/m, $4\pi M_0 = 0.175$ T, $a = 1$ um, $L = 30$ um, and $n = 1$.

3. Conclusions

The obtained results have an interest for the development of ferromagnetic metasurfaces for microwave and terahertz ranges.

Acknowledgements

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References

Metasurface Hologram with High Quality in Microwave Region

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Abstract

Holography has emerged as a vital approach to fully engineer the wavefronts of light since its invention dating back to the last century. However, the typically large pixel size, small field of view and limited space-bandwidth impose limitations in the on-demand high-performance applications, especially for three-dimensional displays and large-capacity data storage. Meanwhile, metasurfaces have shown great potential in controlling the propagation of light through the well-tailored scattering behavior of the constituent ultrathin planar elements with a high spatial resolution, making them suitable for holographic beam-shaping elements. Here, we review recent developments in the field of metasurface holography in microwave region.

1. Introduction

Metasurface, composed of artificially designed metaatoms in sub-wavelength scale, provides an alternative approach for achieving high holographic image quality. By elaborately arranging the geometries of nanoantennas or orientation angles of meta-atoms, desired abrupt interfacial phase shift at designated points within subwavelength thickness can be realized. Therefore, metasurface has been applied to versatile applications, including directional radiators, thin-film cloaking, planar lenses, optical vortex beam generators, and digital holograms. Compared to the hologram based on traditional optical devices, metasurface hologram improves imaging efficiency[1], spatial resolution[2], and robustness against fabrication tolerances[3]. Hence, metasurface holograms have been widely applied in the terahertz, infrared, and visible frequency bands.

2. Design of metasurface holography

Figure 1 shows the hologram based on reflection-type metasurface. To achieve desired hologram, phase information should be encoded on the metasurface, and the phase of each meta-atom on the metasurface can be obtained. When the phase distribution on the metasurface is obtained, the electric field distribution at the focal point can be reconstructed. In order to control the energy distribution at each focal point, weighted holographic algorithm is introduced to adjust the energy distribution among focal points arbitrarily. The weighted holographic algorithm can not only control the number and position of the focal point, but also the energy distribution among the focal points. Figure 1(b) shows the building blocks of reflection-type P-B phase elements used to construct the multi-focus metamirror[4]. The simulated results show that the phase change can cover the whole range of $2\pi$, while the amplitude of the reflection coefficient keeps unity. Based on the proposed P-B phase elements, a multi-focus metamirror and a weighted holographic algorithm, four-focus and five-focus metamirrors are achieved, as illustrated in Fig 1(d), showing good qualitative agreements with theoretical calculations. Figure 1(c) shows the schematic diagram of reflection-type Huygens’ metasurface[5]. By adjusting the $l_m$, $l_g$ and $w_n$, the range of reflection phase can cover the whole range of 360 degrees, while the amplitude of the reflection coefficient keeps unity. A theoretical approach based on spatial energy distribution manipulation is proposed to achieve multi-focus pattern in one-dimensional (1D) space in any desired fashion including focal number, location and intensity distribution, as shown in Fig. 1(e).

Figure 2 depicts the hologram based on transmission-type Huygens’ metasurface[6]. The weighted hologram algorithm is implemented to calculate the interfacial phase distribution on the metasurface. Figure 2(b) shows the schematic diagram of transmission-type Huygens’ metasurface. A split-ring resonator is placed on one face of the dielectric substrate, and an electric-LC resonator is arranged on the other face. By appropriately changing the length $l_e$ and $l_m$ of the resonators, the transmission phase ranges from $-179.89^\circ$ to $178.19^\circ$ and the transmission amplitude varies from 0 to 0.99, revealing the outstanding wave manipulation ability of the designed Huygens meta-atoms, as shown in Fig. 2(d). Based on the transmission-type Huygens’ surface and the weighted hologram algorithm, images of “H,” “I,” and “T” with the uniform focal intensity, and image with specific focal intensity ratio $s_m$ 14:13:12:11:10 are realized and experimentally validated, as shown in Figs. 2(c) and (f). By discretizing the calculated
phase distribution by $2\pi$ over $2\pi$, arbitrary n-bit CHMs can be realized[7]. Based on the coding concept, 1-, 2-, and 3-bits CHMs are designed, fabricated and measured to find the relationship between imaging quality of the CHM holograms and phase-quantization level, as shown in Fig. 2(c). Figure 3 shows the schematic diagram of the microwave three-dimensional imaging[8]. A novel three-dimensional microwave holographic imaging over the [10 GHz - 14 GHz] frequency band with physical implementation and numerical processing is realized utilizing Huygens’ metasurface, as shown in Fig. 3(b), paving the way for 3D broadband display, beam shaping, smart antenna systems and other broadband microwave applications.

Figure 1. Reflection-type metasurface holography. (a) Diagram of reflection-type holographic imaging[4]. (b) Structure of reflection-type P-B phase meta-atom[4]. (c) Structure of reflective-Huygens meta-atom[5]. (d) The measured results of holographic imaging based on P-B phase metasurface[4]. (e) Single focus imaging at any position, dual-focus imaging at any position and dual-focus imaging with arbitrary focal intensity control based on Huygens’ metasurface[5].

Figure 2. Transmission-type metasurface holography. (a) Diagram of transmission-type holography[6]. (b) Schematic view of the proposed Huygens meta-atom[6]. (c) The images of "H", "I" and "T", respectively, based on Huygens metasurface[6]. (d) Transmission characteristics of Huygens meta-atom[6]. (e) Four-focus holographic imaging of Huygens metasurface[7], based on 1, 2 and 3-bit coding metasurface. (f) A weighted "I" image with a specific focus intensity distribution[6].

Figure 3. (a) Schematic diagram of the microwave three-dimensional imaging utilizing Huygens’ metasurface[8]. (b) Experimental results of electric field intensity distribution in three planes. (a) 12 GHz. (b) 10 GHz. (c) 14 GHz

3. Conclusions

In conclusion, we have briefly summarized our recent progress on hologram with reflection-type and transmission-type metasurface. These research outputs have offered metasurfaces significantly expanded capabilities to control EM waves in microwave regimes, providing a promising platform to realize microwave applications for holographic technologies.

References

Plasmonic Nanomaterials for Bio-diagnostics, Environmental Monitoring and Food Safety
Novel requirements for bioanalytical methods emerge due to trends such as personalized medicine. Other applications can be found in bioanalytics, such as the screening for pathogens in the environment or in food. Beside the detection of pathogen species, also the study on the presence of antibiotic resistance genes is of growing interest and is another application for molecular detection technology development. In conclusion, innovative tools for diagnostics and bioanalytics are needed, to be usable outside of dedicated laboratories and with less qualified personnel, at minimal costs.

Plasmonic nanostructures promise to provide sensing capabilities with the potential for ultrasensitive and robust assays in a high parallelization, and without the need for markers. Upon binding of molecules, the localized surface plasmon resonance (LSPR) of these structure is changed, and can be used as sensoric readout [1]. This is possible even on a single nanostructure level, using optical darkfield detection introduced more than 100 years ago [2], as demonstrated for DNA detection [3]. In contrast to SPR, LSPR senses only in a very thin layer (on the scale of the particle diameter), resulting in an efficient background suppression [4].

In order to multiplex this approach, an imaging spectrometer based on a Michelson interferometer has been developed, able to readout a whole array of sensors in one step [5]. On the sensor side, microarrays of gold nanoparticle spots were fabricated using spotting of presynthesized gold nanoparticles [6]. Such chemically synthesized particles allow for a cost-efficient generation of highly crystalline particles as nanosensors; by using microfluidic approaches, a high quality and reproducibility can be achieved [7]. The functionalization of the various particle spots is realized by spotting thiolized DNA onto each spot separately. Using this approach, a multiplex DNA-based detection of fungal pathogens involved in sepsis could be demonstrated [8].

References
Plasmonic tools to study interactions relevant for food science and eco/nanotoxicology

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Abstract
Nanosized sensors based on the local refractive index sensitivity of plasmonic nanostructures can be applied to study interactions occurring at biointerfaces relevant for understanding protein effects in eco and nanotoxicology and in food science. Plasma protein interactions with silver nanoparticles modulate the biotransformation of silver to silver sulfide while saliva proteins coupled to plasmonic sensors can be used to quantify astringency through interactions with polyphenols.

1. Introduction
Metallic nanostructures supporting plasmon resonances are proposed and applied as enabling materials for bio and chemical sensors. Refractive index sensing structures at structures with appropriate functionalization can be applied for detection of molecules and bacteria through specific interactions \([1,2]\). For some applications such as in the food area, non-specific interactions or aggregate interactions from many different poorly specific interactions are responsible for important and measureable effects (such as sensations) requiring mimicking interfaces to provide useful sensing function. Measuring of astringency in foods and wines is complicated process typically carried out by panels of tasters and develops over the lifetime of the food. Here quantifying of specific (bio)molecules does not typically give a measure of the effect since it is an aggregate effect from many components. Plasmonic sensors can be used as multifunctional sensors allowing both refractive index measures and other spectral readouts. Here different plasmonic elements will be described as well as functionalization with biomolecules or molecular imprinted polymers to allow the study of both specific and non-specific interactions. Chiral plasmonic elements can provide resonances visible in CD spectra that can be used to enhance sensor readout \([3,4]\). Hole mask colloidal lithography \([5]\) combined with programmable angle controlled PVD deposition can be used to make complex plasmonic elements over large areas and has been applied to create chiral and non-chiral elements \([6]\).

2. Results and Discussion
Examples of sensor development and designs relevant for food science and eco and nanotoxicology will be given. The first will relate to quantifying astringency in wine. Quantification of interactions of polyphenols with saliva proteins can be carried out via refractive index readout and correlated to conformational change of the proteins which are the initial steps in the sensations caused by astringency \([1]\). Approaches to capture biomimetic saliva coatings via MIPs allow both the classification of wines but also the study the role of individual polyphenol components from wine in causing astringency \([7]\). A second example will involve quantification of protein and biotransformations relevant for nano and ecotoxicology where weak and strong interactions of proteins at different sites of silver nanocubes are studied via plasmon resonances \([8]\) and related to biotransformations altering nanoparticle cytotoxicity \([9]\).

3. Conclusions
Plasmonic elements can provide insight into interactions occurring close to the metal surfaces. These can be applied in scientific studies in the areas of food science and nanotoxicology or as biosensor elements providing quantitative readout.

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References


Towards label-free, implantable neuro-plasmonic probes

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Abstract

Optical fibers are widely applied to stimulate and monitor neural activity in deep brain regions expressing light-sensitive genetically-encoded sensors and actuators. Recent progress has demonstrated that these probes can be used to perform endoscopic imaging and depth-resolved tissue interrogation. However, label-free sensing of neural events in vivo is still beyond the reach of currently available technologies. To remediate this shortcoming, we have developed novel methods to fabricate multiple plasmonic bio-sensors on the optically active surface of flat-cleaved and tapered optical fibers.

1. Introduction

Owing to the development of genetically-expressed actuators and indicators of neural activity based on light sensitive proteins, the advent of optics and photonics in neuroscience has enabled revolutionary experimental approaches [1], [2]. This has driven the growth of a related field, known as neurophotonics, that is providing researchers with powerful optical methods[3]. In this context, optical fibers are widely used to interface with deep brain regions that lie beyond the reach of common imaging systems. Recent work has demonstrated that harnessing modal propagation in multimode optical fibers opens the door to endoscopic imaging at the fiber tip[4] or to depth-resolved light delivery and collection along mm-long tapered optical fibers[5], [6]. However, the application of these advanced methods to translational studies is hindered by the need of genetically-encoded fluorescent molecules. To circumvent this drawback, we have developed a novel class of implantable neurophonic probes that have the potential to exploit light-matter interaction at the nanoscale to achieve label-free optical neural interfaces.

2. Results

The microscopic cross section of a fiber tip, together with its inherent light-coupling, makes it an attractive platform to support sensing elements. However, this same feature is hardly compatible with established nano-patterning technologies that have matured on large, planar substrates. To address this, we developed an effective Focused Ion Beam (FIB) fabrication process to pattern planar and highly-curved optical fibers’ surfaces.

As a first step, we optimized the fabrication of 2D nanoplatelet arrays (NPA) with FIB milling in a gold film deposited on a borosilicate glass microscope coverslip. The process involved two steps. First, a 5-nm thick adhesion layer of Cr and a 180 nm-thick layer of Au were deposited on a thin glass substrate via thermal deposition. In accordance with McPeak et al. [15], the deposition was performed at a rate of 1 Å/s, with chamber pressure of 6*10-6 mbar. Second, NPA were carved in the gold layer by milling thin slits of metal with a Ga2+ FIB (FEI dual-beam HeliosNanoLab600i) system. This resulted in 30 µm×30 µm wide arrays with sharp, tapered grooves (Fig.1) that show clear resonances in the reflectivity spectrum (Fig.2).

![Figure 1: SEM image of nano-platelet array fabricated via FIB milling on a thin gold layer (150 nm) deposited on glass. Grating period is 640 nm, platelet separation ~ 30 nm. Scale bar is 1 µm.](image)

Then, we translated this process on the tip of a multimode optical fiber (core size 50 µm, NA 0.22) and we fabricated arrays of nano-holes (NHA) (Fig.3) with 200 nm diameter (Fig.4). Finally, we adapted the fabrication method to pattern 2D nanoplatelets arrays on the highly curved surface of a tapered fiber covered with a thin layer of gold (150 nm). This led us to obtain multiple NPA with sub-wavelength gaps distributed along the fiber surface.
3. Conclusions

In light of the versatile optical properties of tapered fibers, we view this strategy as a promising method towards spatially-selective, plasmonic neural interfaces with deep brain regions in vivo.

References

Hybrid Plasmonic Nanomaterials: Functional Platforms for Bio and Food

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Abstract

We analyze absorption spectra of spherical gold nanoparticles embedded in polyethylene glycol diacrylate. The designed wearable platforms could detect specific target analytes in localized surface plasmon resonance and fluorescence modes. The proposed fabrication strategy represents a good candidate for becoming a functional platform for Bio and Food screening.

1. Introduction

Localized Surface Plasmon Resonance (LSPR) based biosensors have received increasing interest in the recent years, due to their unique advantages compared to other sensing technologies. These benefits include single-molecule sensitivity and the possibility to scale down the whole detection setup. LSPR biosensors are based on the presence of nanostructures, whose dimensions are much smaller than the excitation light wavelength. We propose an optical platform based on bottom-up chemically synthetized spherical gold nanoparticles (Au-NPs) embedded in Poly-(ethylene glycol) diacrylate (PEGDA). As a hydrogel, PEGDA represents a biocompatible, flexible, transparent material that can be used as a substrate for creating wearable, 3D, plasmonic biosensors [1]. The optimization of the LSPR response of such device could be coupled with another well-known phenomenon: the Plasmon-Enhanced Fluorescence (PEF), obtaining a dual-mode diagnostic tool for performing Immunometric immunoassays [2] for the detection of cancer biomarkers, immunoglobulins and viruses, as well as screening of toxins in food. Au-NPs/PEGDA platforms can be used to achieve continuous, real-time monitoring of the targets on non-planar surfaces.

2. Fabrication and Optical Characterization

To obtain a flexible system, we embed Au-NPs in PEGDA (MW=700 Da). It is possible to tune the performance of the flexible sensor by varying the PEGDA hydrogel mesh size, as well the concentration of the AuNPs (Fig.1). Colloidal Au-NPs were prepared with a bottom-up approach, stabilized with Citrate (Seed and Growth synthesis [3]), and then embedded into/onto PEGDA (polymerized through UV-light exposure). The fabrication process scheme is reported in Fig. 2.

3. Discussion and Conclusions

The optical characterization of these novel nanocomposite materials shows very promising results. In fact, we obtained a large-scale, cost-effective and flexible material and we successfully detected Biotin conjugation. Next step will be the coupling of the functionalized plasmonic sensor with a specific labelled target, to exploit Plasmon-Enhanced Fluorescence.

References

Plasmonic nanostructures for label-free detection of water contaminants

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Abstract

The study of novel plasmonic nanopatterns is of great interest for different applications including chemical sensing. In this work we design, fabricate and characterize novel periodic arrangements of gold nanoelements. We tested the detection performance of our nanostructures analyzing different concentrations in water of fipronil and imidacloprid insecticides using both the Localized Surface Plasmon Resonance (LSPR) and Surface Enhanced Raman Spectroscopy (SERS) sensing approach. Our results suggest that these plasmonic patterns are promising to develop nanosensors for the detection of water contaminants with high sensitivity.

1. Introduction

Development of nanostructures based on plasmonic functionalities is of great interest for a range of applications including sensing, optoelectronic devices and platforms to improve their performance in spectroscopic measurements [1, 2]. In sensing devices their ability to confine high electromagnetic field has been used to detect biological and chemical analytes or environmental contaminants in general. Systems based on nanopillars or nanocavities have been designed according to their geometrical features leading to enhanced responses in plasmonic devices. Plasmonic properties associated to the nanostructure can be tuned by changing the size and the shape of the individual nanoparticles or the periodicity or, more in general, the geometry of the nanopattern. These features are keys to many applications aiming at signal enhancement and low threshold sensing. In this work we present a study of novel periodic arrangements of unit cells made of gold nanopillars. Nanostructures analyzed were fabricated using electron beam lithography technique (EBL) which allows creating patterns with high accuracy and repeatability. Morphological analysis was realized by Scanning Electron Microscopy (SEM) and their plasmonic properties were studied and compared using experimental set-up for Localized Surface Plasmon Resonance (LSPR) and Surface Enhanced Raman Spectroscopy (SERS). We tested the sensing performance of our nanostructures analyzing low concentrations of fipronil (C₁₃H₁₁Cl₅F₂N₂O₅S) and imidacloprid (C₁₈H₂₆ClN₃O₂) insecticides in water, widely used in agriculture, that can cause serious diseases in humans and animals. Our preliminary results suggest that the plasmonic nanopatterns considered are promising to develop devices for a rapid, label-free and high sensitive detection and, in addition, can be integrated in on-chip devices to realize portable point-of-care tools.

2. Materials and methods

2.1. Nanostructure fabrication and morphological characterization

We fabricated nanostructures based on different unit cells by using an EBL system (Raith 150). The unit cells taken into account consist of gold nanopillars with 1) iso-Y shape with branches of size 100 nm (figure 1a) and 2) the fusion of three equilateral triangles with side size of 300 nm (figure 1b). We realized periodic arrangements of these unit cells on glass substrate with different minimum interparticle distance (mid) of the unit cell. In all cases, the dimension of the pattern was 300x300 µm. The nanostructured substrates were fabricated through the use of the conventional procedure of the EBL fabrication described in previous works [3, 4]. Nanostructures have been morphologically characterized by the use of SEM (Raith 150) (Figure 1).

Figure 1: SEM images of the nanopatterns based on NPs with two different unit cells fabricated by EBL: a) iso-Y geometry and b) fusion of three equilateral triangles.
2.2. Plasmonic measurements

Spectroscopic characterization performed by Vis-NIR extinction measurements allows to investigate the characteristic LSPR of the nanostructures. We used the same set-up reported in a previous work [5]. In the set-up, unpolarized white light of a halogen lamp is focused on the nanostructure and the transmitted signal is coupled in a fiber (core = 50 µm) positioned behind the sample and connected to a spectrophotometer (Ocean Optics USB4000). SERS measurements were realized by using the QE Pro Raman system (Ocean Optics) with a grating of 1200 lines/mm and configured for a laser wavelength of λ = 785 nm. The system is coupled with an upright microscope Olympus BX51. Spectra are collected in the range 400–1800 cm⁻¹ by using a laser power of 12 mW, 10 s of integration time and a 50X (N.A. = 0.75) microscope objective. Using these set-up we tested our nanostructures to detect different concentrations ranging from µM to nM of fipronil and imidacloprid in distilled water.

3. Discussion

In figure 1 are reported the SEM images of the nanopatterns fabricated. Images highlight how the characteristic sizes of the patterns are uniform and regular on the whole substrates fabricated. For both geometries, we measured their LSPR bulk sensitivity m evaluating the LSPR peak shift achieved for H₂O/IPA solutions with different refractive index: H₂O (n=1.332), IPA/ H₂O 1:10 wt/wt (n=1.341), IPA/ H₂O 1:5 wt/wt (n=1.349), IPA/ H₂O 1:1 wt/wt (n=1.364), and IPA (n=1.374). We found values higher than 400 nm/RUI for both geometries. Subsequently, we evaluated the Limit of Detection (LOD) of ours nanopatterns for a specific detection of two insecticides taken into account, imidacloprid ((C₆H₁₀ClN₃O₅) and fipronil (C₁₂H₁₇Cl₂F₄N₂O₅S), and using the same LSPR sensing platforms (figure 2a and 2b). We functionalized the substrates using antibodies appropriate for the two insecticides. Moreover, preliminary SERS analysis of the two analytes was performed. In figure 2c is reported the spectra achieved in the case of a concentration of imidacloprid of 5 µg/ml. Our preliminary results highlights how the nanopatterns analyzed can be useful for a detection of the two insecticides up to concentrations in water of the order of a few nM.

4. Conclusions

In this work we have conceived novel nanostructures that can be used as conventional plasmonic tools of detection. Our nanostructures have shown interesting results in the analysis of low concentrations in water of two different insecticides largely used in agriculture. Our achievements indicate how these patterns can be employed to realize high sensitive devices for low-cost portable point-of-care diagnostics useful for detecting low concentrations of water contaminants.

![Figure 2](http://example.com/figure2.png)

Figure 2: Sensing evaluations: LSPR peak shift achieved in the case of a) different concentration of Imidacloprid using the pattern in figure 1a and b) different concentration of Fipronil using the pattern in figure 1b. c) SERS spectra achieved in the case of a concentration of 5 µg/ml of imidacloprid.

Acknowledgements

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References

Pixeled metasurface for multiwavelength detection

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Abstract

We present a plasmonic biosensor based on surface-enhanced infrared absorption spectroscopy (SEIRA), which exploits resonant coupling between plasmonic nanoantennas and vibrational excitation of small molecules. Specifically, our proposed platform features a large-area (several mm²) metasurface made of gold nanoantennas fabricated on a silicon substrate, comprising different macrorregions (“pixels”) of area 500×500 µm². As a result, a single chip is capable of performing analysis from the region of functional groups to that of fingerprint. Our experiments demonstrate the capability to detect a concentration as low as 86 pmol/L of a small molecule which is the best marker of vitamin D3 (25(OH)D3).

1. Introduction

The detection of molecules at extreme low concentrations is a problem of crucial relevance and impact not only in the fields of medicine and pharmacology, but also for emerging applications such as trace chemical detection, homeland security, food safety and forensic sciences. Among the various approaches, far-field mid-infrared (MIR) spectroscopy is a standard analysis technique for detection and identification of molecules, via their own characteristic absorption spectrum, in a univocal, non-destructive and label-free fashion. In particular, complex vibrational absorption spectrum, in a univocal, non-destructive and label-free fashion. In particular, complex vibrational characteristics of molecules in bulk materials occurring within the so-called “fingerprint” region (1500–600 cm⁻¹ in wavenumber, ~6–16 µm in wavelength) can be effectively distinguished via MIR spectroscopy, thereby enabling unambiguous identification of molecular structures and species. However, because of the very low molecular absorption cross-section of infrared vibrations this technique fails at extremely low concentrations [1]. One such way to achieve signal amplification is surface-enhanced infrared absorption (SEIRA) spectroscopy, which exploits metallic nanoantennas (NAs) supporting localized surface plasmon resonances (LSPRs) to enhance light-molecule interactions in the MIR range [2]. Here, we report on the experimental detection of 25(OH)D3 by exploiting plasmonic metasurfaces based on 2-D arrays of gold NAs on a silicon substrate. The coupling between neighbor NAs ensures a significant near-field signal enhancement. In particular, we design a large area (several mm²) pixeled metasurface, with different pixels engineered so as to operate within separate spectral ranges, from the region of functional groups to that of fingerprint. Thanks to the combined collective and individual NA plasmonic responses, we attain large signal enhancement factors within the range 10⁻¹⁻¹⁰. By relying on a new geometrical design, we are able to improve the sensitivity and to detect concentrations as low as 86 pmol/L, and amounts of immobilized small molecules of 25(OH)D3 (with molecular weight, MW: 418.65 Da) as low as 0.174 amoles over an area of 100×100 µm².

2. Design, Fabrication and Functionalization

The modeling and design of the metasurfaces in this study relied on full-wave numerical simulations carried out via the finite-element-based commercial software package Ansys HFSS electromagnetics suite 16.2 [3]. In our simulations, the metasurfaces were modeled as 2-D periodic arrangements of gold NAs (of thickness t = 50 nm) laid on a silicon substrate. In view of the periodicity, only a single unit cell was simulated, by assuming normally incident plane-wave illumination from air, with master/slave periodicity conditions enforced at the lateral walls. We have explored two different design cross-shaped (CS) NAs and Star-shaped (SS) NAs. The results confirm that it is possible, via judicious choice of the geometrical parameters, to broadly tune the position and linewidth of the resonance peak over the spectral range of interest. The proposed gold NAs have been fabricated on a silicon substrate by means of Electron Beam Lithography and lift-off process. In particular, 500×500 µm² pixels have been disposed into a matrix scheme (see Fig. 1) [4]. To detect the capture of 25(OH)D3 on the chip surface, we used an immunoassay, i.e., we used a highly specific anti-25 hydroxy D antibody. This concentration was chosen by assuming that all antibody
molecules were adsorbed on the gold surface and that a single monolayer of closely packed antibody molecules (average diameter 200 Å) was formed. Binding measurements were performed following the procedure described above, by using 25(OH)D3 at concentrations of 600 ng/ml, 60 ng/ml, 36 ng/ml.

Figure 1: Schematic of the pixeled metasurface. a) Schematic design of the pixeled metasurface; SEM image of a CS pixel (b) and of SS pixel (c).

IR measurements were performed using a Perkin Elmer Spectrum One FTIR spectrometer, with a spectral resolution of 4 cm⁻¹ by collecting, at room temperature, the reflected signal within the spectral region 4000-600 cm⁻¹, by using 128 scans with 5s acquisition time for each spectrum. All acquired spectra were automatically normalized to a background spectrum pertaining to a flat unpatterned gold layer (of same thickness as the NAs) deposited on the same substrate.

3. Discussion

Our engineered pixeled metasurface enables to explore both the functional group and fingerprint regions on the same substrate, by utilizing the same functionalization steps. A reference analytical characterization of the 25(OH)D3, via FTIR analysis of a solid-form sample, has been utilized in our experiment to identify the presence of the 25(OH)D3 on our pixels through the comparison of the characteristic vibrational bands. The gold NAs were functionalized with the antibody solution, and the FTIR spectra were examined before and after the antibody adsorption on their surface, and again after the binding with the 25(OH)D3. The amount of antibody adsorbed on the whole chip area of 1 cm² was estimated to be 442 fmol. Considering an area coverage exposed to the light of 100×100 μm², we were able to detect in a single measurement 44.1 amoles of antibody. All the pixels exhibited values of sensitivity between 500 and 800 nm/RIU in terms of resonance shift. SEIRA detection enabled us to determine the presence of 25(OH)D3 at extremely low concentration. The lowest concentration of 25(OH)D3 that could be detected with the CS design was 60 ng/ml (143.33 nmol/L), and the number of molecules linked to an area of 100×100 μm² was 71.5 pmoles. For the SS design, design (with hexagonal lattice), which exhibits a double number of tips for the same area coverage, concentrations as low as 86 pmol/L and an absolute amount of 25(OH)D3 as small as 0.17 amoles could be detected. Our proposed pixeled metasurface is not only capable of detecting extremely low concentrations of analyte, but it also provides attractive advantages with respect to traditional methods based on radioactive compounds, that are time- and reagent-consuming, and require disposal, pretreatment procedures and expensive instrumentation [5].

This metasurface was functionalized with a concentration of 25(OH)D3 as low as 36 pg/ml (86 pmol/L), i.e., well below the minimum threshold reached by the methods used nowadays and below the clinically relevant levels.

Figure 2 SEIRA spectra: a) CS pixel with L = 2.3 μm, W = 200 nm and P = 2.5 μm; b) SS pixel with L = 1.0 μm, W = 110 nm and P = 1.7 μm.

4. Conclusions

By using a pixeled plasmonic metasurface, we have experimentally demonstrated the multiwavelength detection of 25(OH)D3, which is the most common marker of vitamin D3. Each pixel of the metasurface supports LSPRs tuned to different parts of the MIR spectrum by varying the geometrical parameters. Specifically, we evaluated two NA designs. For the CS design, we observed the best performance in terms of EF for the pixel having the smallest gap (200 nm) between adjacent arm tips (EF = 2.2·10⁵). In this case, the minimum detected concentration was 143.32 nmol/L, and the number of molecules linked to an area of 100×100 μm² was 71.5 pmol. For the SS design, design (with hexagonal lattice), which exhibits a double number of tips for the same area coverage, concentrations as low as 86 pmol/L and an absolute amount of 25(OH)D3 as small as 0.17 amoles could be detected. Our proposed pixeled metasurface is not only capable of detecting extremely low concentrations of analyte, but it also provides attractive advantages with respect to traditional methods based on radioactive compounds, that are time- and reagent-consuming, and require disposal, pretreatment procedures and expensive instrumentation [5].

References

Light-induced Aggregation of Gold Nanorods on Graphene controlled by Radiation Pressure for SERS Detection of Biomolecules

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Abstract

Radiation pressure is used to push gold nanorods on multilayered graphene and create hybrid active surfaces for Surface-Enhanced Raman Spectroscopy (SERS) in liquid. As a proof of concept, ultrasensitive detection of bovine serum albumin (BSA) is shown, and the aggregation kinetics is studied as a function of the irradiation time. Our results enlarge the spectrum of materials that can be used for optical aggregation and SERS detection of biomolecules, highlighting the importance of controlling the physical properties of the surfaces.

1. Introduction

Optical tweezers exploits optical forces to control nano-objects in liquid environment. The mechanical effects of focused laser beams on a particle can be described by two main contributions, a conservative force, responsible for confining the particle around the focal region of the laser beam, and a dissipative one, responsible for pushing the particle along the laser beam propagation direction [1]. The competition of these two components determines if the particle is stably trapped within the laser spot or if it is scattered away along the laser beam direction. Optical tweezers can be integrated with spectroscopic techniques such as Raman spectroscopy [2], enabling chemical characterization of individual micro and nano particles in liquid. Optical manipulation of metal nanoparticles (MNPs) is of particular importance. Localized surface plasmon resonances (LSPR) [3], in fact, make MNPs act as antennas at optical frequencies [4] and the large electromagnetic fields present at the MNPs surface can be exploited for ultrasensitive molecular analysis, such as it happens in Surface Enhanced Raman spectroscopy (SERS) [5], which provides signal amplifications up to ten orders of magnitude [5].

The combination of optical forces with plasmonic effects allows one to tailor ultrasensitive SERS detection in liquid environment [6,7] in a contactless, chemical-free way: the so-called LIQUISOR concept [8,9]. LIQUISOR detection has a unique advantage in the analysis of highly diluted samples which irreversibly modify their physical/chemical properties and functionality when dried, e.g. biomolecules. SERS in liquid takes advantage of the huge fields’ amplification at the nanogaps among closely spaced particles (hot spots) [5]. Optical forces and radiation pressure can be exploited to create SERS hot spots nearly on-demand, by either optically trapping/positioning [6] or aggregating MNPs [7,8] in a solution containing the target molecules. Efficient LIQUISOR detection requires efficient plasmonic colloids and a precise control of the forces that come into play. More recently, the nature and geometry of the substrate on which aggregation is carried out has turned out to play an important role [10]. In this context graphene [11] can play a relevant role when implemented in the laser induced formation of SERS-active aggregates in-liquid. Graphene, thanks to the quenching of the photoluminescence and chemical enhancement effects, can be used as an active substrate for Raman. Moreover, graphene has an excellent electron and thermal conductivity enabling very efficient heat dissipation, which may prevent or slow down the occurrence of bubbling and turbulence effects [11]. Here we show proof-of-concept results on the possibility to optically aggregate gold nanorods on graphene surfaces and carry out SERS spectroscopy of BSA dispersed in the liquid solution.

2. Results and Discussion

Experiments are carried out irradiating with a NIR laser (785 nm) a colloidal dispersion of gold nanorods mixed up with BSA at 0.1 mM, i.e. a concentration ten times lower than its limit of detection (LOD) by conventional Raman. Upon mixing, BSA molecules substitute the CTAB layer around the AuNRs, acting as a new stabilizing agent for the gold nanostructure and thus forming new scattering objects, i.e. BSA-AuNRs complexes (BSA-AuNRCs), which at 10⁻² M are stable in time [8,9]. The laser focus is located inside the colloidal solution just few microns above a multilayered (ML) graphene substrate. After highlighting the overall dissipative regime of our experimental conditions, we discuss the aggregation dynamics properties observed with and without graphene.

As previously reported [8], we can distinguish an onset where the first Raman peaks starts to appear over the background signal, a stage where the SERS signal steadily increases and a final saturation, due to the fact that, once BSA-AuNRCs have completely filled the laser focus...
volume, the addition of further nanoparticles to the aggregate has no influence on the collected SERS signal. After the aggregation process a stable aggregate is observed on the graphene surface. The SERS signal dynamics is studied by plotting the Phe peak intensity after background subtraction, as a function of the irradiation time. The data follow a sigmoidal trend which can be modeled by a Boltzmann growth kinetics [7, 9-11]:

\[
A(t) = \frac{A_1 - A_2}{1 + e^{(t-t_0)/\tau}} + A_2,
\]

where \( A_1, A_2 \) are the initial and final values of SERS intensity, respectively, while \( t_0 \) represents the time at which the signal reaches half of the saturation value, and \( \tau \) is related to the slope of the curve at \( t = t_0 \). Typically, \( A_1 = 0 \) because there is no aggregation without laser illumination at \( t = 0 \). The comparison made with an analogous process carried out on a glass substrate in the same experimental conditions, highlights the same trend observed for aggregation on graphene, but on different time scales. The whole aggregation process on glass is about 3.5 times faster than on graphene [11]. A further comparison was attempted investigating the possibility to carry out aggregation on gold surfaces. Here the trapping process results much unstable with no trace of stable aggregates in the optical images of the substrate after several tens of minutes of light irradiation. Spectra exhibit a variability not observed on the previous substrates, with the appearance of new fluctuating peaks over a background of variable intensity and shape. During the process we also observe spectra with an increasing broad background centered on the Raman bands around 1300 and 1600 cm\(^{-1}\), typical of amorphous carbon, and exhibiting peaks that fluctuate over time in intensity and position. Amorphous carbon bands indicate rapid degradation of the molecule. The appearance of different Raman peaks is typical of fast modifications of the protein structure.

We attribute the differences among the various substrates (graphene, glass, gold) to the destabilization effect of the standing wave trap, with equilibrium positions outside from the surface, produced on the metallic substrates, due to their higher reflectivity, and to the reduced thermophoretic effects, related to the higher heat dissipation [11].

3. Conclusions

In conclusion we have shown the possibility to exploit the radiation pressure to aggregate plasmonic nanorods on graphene and carry out in-liquid SERS detection of BSA (0.1 mM). Compared to glass, the aggregation kinetics on graphene is slower. The larger hydrophobicity of graphene, the generation of a standing wave trap and the higher thermal conductivity are likely the causes of the depleted thermophoretic forces and of the consequent slowdown of the aggregation process and the generation of smaller aggregates compared to glass. The optical and thermal properties of the surfaces turn out as key factors driving the process dynamics [11]. However, despite the slowdown of the aggregation kinetics, the usage of graphene as substrate offers manifold benefits: an almost negligible fluorescence background when using near-infrared light (785 nm), the absence of thermal absorption as well as the possibility to easily functionalize the surface to enhance the affinity with the analytes, representing an ideal and seamless platform to integrate in (bio)sensing applications, easily integrable in microfluidic systems [12].

Acknowledgements

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References


Enhanced Refractive Index Imaging Based on Quasi-Bound States in the Continuum

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Abstract

We achieve a condition of enhanced hyperspectral refractometric imaging on all-dielectric photonic crystal slabs (PhCS) using a scheme of surface-enhanced fluorescence (SEF) combined with refractometric sensing. The scheme is based on two high-\(Q\) resonances in proximity of bound states in the continuum (BICs). The mechanism of quasi-BIC spatially-variant gain, tracked by quasi-BIC refractometric sensing, can find application in many fields for monitoring physical and biochemical processes. In this study, it is applied for surface cell analysis.

1. Introduction

Recently, photonic bound states in the continuum (BICs) have attracted large interest. A BIC is a special mode in the energy continuum of free space waves that cannot couple with free-space radiation, which leads to a diverging radiative \(Q\)-factor and a topological singularity in the reciprocal space \([1, 2, 3]\). Our group demonstrated several applications of BICs for surface amplification of fluorescence emission and Raman scattering \([4]\), spin-optical transport \([3]\), biological and chemical sensing with capability of detecting ultralow-weight molecules \([5]\) and protein traces \([6]\).

Here, we present our recent research \([7]\) and discuss a synergistic hyperspectral imaging which combines surface-enhanced fluorescence (SEF) and spectroscopic refractometric sensing based on two high-\(Q\) resonances of a dielectric PhCS, in proximity of an accidental and a symmetry-protected BIC.

2. Results

The local optical field of the first resonance can enhance of two orders of magnitude the SEF emission of a probe dye but is maximized only when the RI on top of the PhCS matches a target value, corresponding to the specimen of interest. Simultaneously, spatially variant spectral position of the Fano resonance between second mode and fluorescence emission is used to measure the local refractive index, after proper calibration, during the raster scan. Since the spectral matching between first resonance and input laser is modulated by the specimen local refractive index, this tuning is used to have an enhanced readout of the RI variation based on the corresponding variation of SEF. Correlative refractometric maps with a resolution of \(10^{-5}\) RIU within femtoliter-scale sampling volumes is obtained also on live prostate cancer cells grown on the PhCS.

A scheme of the cavity-enhanced SEF with space-variant refractive index, \(n_e(x, y)\), is shown in Fig. 1a-b. The high-\(Q\) resonances are respectively used as fluorescence \(pump\) mode 1 and refractometric \(probe\) mode 2. A dye molecular layer is suitably bonded on the PhCS surface. Input laser and mode 1 matching is maximized at the target RI of the specimen (Fig. 1b) in proximity of an emerging accidental BIC. Concurrently, mode 2 culminates with a symmetry-protected BIC and belongs to a nearly flat-dispersion band over broad angular range, which gives a Fano profile in the SEF spectrum of the dye and is tracked to correlate SEF gain and local RI variation. In this way, the peak wavelength shift due to the RI variation is converted into a more sensitive readout based on photoemission intensity.

In particular, like mentioned above, RI imaging is investigated on prostate cancer cells (PC3 line) cultured directly on the PhCS \([7]\). It is largely known that cancer onset deeply affects internal cellular organization. Due to higher amount of proteins, cancer cells are typically characterized by a higher RI than normal cells. Spatially averaged RI of cancerous cells ranging from 1.392 to 1.401 has been reported, against normal-cell RI ranging from 1.350 to 1.370. The enhanced RI mapping is demonstrated with raster scans of the surface RI of PC3 cells using a PhCS designed to work around 1.397 RIU. An example of RI imaging is shown in Fig. 2. The RI map is actually reconstructed from the SEF intensity map acquired in correspondence of a cell, a conversion that can be made \(via\) a calibration curve measured with certified RI liquids. In Fig. 2, the optical intensity features produced by light scattering and absorption are related to the fluctuations of real and imaginary RI, mainly reflecting organelles and lipid droplets dispersed anywhere in the volume of the cell. Details on designing the resonances of the PhCS, calibration measurements and enhanced SEF readout will be presented on site.
Figure 1: a) Sketch of the sample. b) Schematics of the enhanced RI measurement: the SEF enhancement of the probe dye depends on the local RI variation of the specimen because it affects the laser and pump resonance spectral matching (left panel) and is tracked in real time by the Fano dip produced by the second probe resonance in the same SEF emission (right panel).

3. Conclusion

The enhanced RI readout based on SEF gain allowed us achieving a resolution potential of the order of $10^{-5}$ RIU over a large and transparent sensing area providing the possibility of mapping the spatially-variant surface refractive index of live cells, in microscopy configuration. We foresee to apply this approach for studying many other physical, chemical and biological processes.

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References


PHOTOMETRIC STATION FOR IN-VITRO DIAGNOSTIC ANALYSIS USING ORGANIC-BASED OPTO-ELECTRONIC DEVICES AND PHOTONIC CRYSTALS

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Abstract

A method and an apparatus for carrying out in vitro diagnostic analysis of biological samples by analyzing the spectrum of light radiation transmitted through the sample, using innovative components for this analysis was developed. The in-vitro analysis systems currently available, for example for the ELISA (enzyme-linked immunosorbsent assay) test, usually employ a halogen lamp or LEDs as a light source, optical fibers as transmission media for the optical path, a set of mechanically selectable optical filters, and photo-sensors for reading the signal intensity. In particular, interference filters and inorganic solid state photodiodes are commonly used. These systems, usually, have the following restrictions to be respected: maximum reading range from 0 to 3 Optical Density (OD), 5 different probing wavelengths: 405nm, 450nm, 492nm, 550nm, 620 nm, bandwidth for each wavelength around 10nm. The system proposed in our work is based on Organic Light Emitting Diodes (OLEDs) with broad emission spectrum for white light and on a series of Photonic Crystals (PCs) that selects the needed probe wavelengths (405 nm, 450 nm, 492 nm, 550 nm, 620 nm) and a bandwidth of around 10 nm around the peaks, for an acquisition sensitivity from 0 to 3 OD. A very compact optical path has been designed. The detection of the signal is carried out using an Organic Photodiode (OPD) having an appropriate photosresponse. The design of the proposed system gives the opportunity to reduce the overall dimensions of the analyzer, compared to the systems existing on the market, avoiding the use of additional optical fibers, interference filters and optical losses.

1. Introduction

Among the secondary effects due to the sudden globalization, accompanied by important migratory flows, there is the continuous development of infectious diseases which, especially in less than optimal health conditions, require both early diagnosis and adequate prevention and treatment. This health picture is one of the main factors that amplify the demand for immunological analyzers and compact consumer products in the diagnostic-health sector as it has been happening in recent months with the advent of the COVID-19 emergency.

In particular, serology testing for SARS-CoV-2 is at increased demand in order to better quantify and classify the COVID-19 cases. With serology test, it is possible to include peoples that may be asymptomatic or have recovered. These are blood-based tests that can be used to check if people have been exposed to a particular pathogen by looking at their immune response. In contrast, the RT-PCR tests [1], that currently are adopted to diagnose COVID-19 cases, can only indicate the presence of viral material during infection and will not indicate if a person was infected and subsequently recovered. These tests can give greater detail into the prevalence of a disease in a population by identifying individuals who have developed antibodies to the virus, also to create a database that also allows better use of blood plasma treatments. This type of tests must utilise systems that allow enzyme to detect the presence of particular antibodies or antigens in biological sample as in ELISA - Enzyme Linked Immunosorbsent Assay test [2].

The systems currently available in the state of the art for this type of test use spectrophotometric systems based on halogen lamps or LEDs as a light source, optical fibers as transmission means in the optical path, a set of mechanically selectable filters and photosensors for reading the signal strength.

The industry in the sector is growing rapidly thanks to the introduction and constant adoption of automated and advanced techniques for laboratory instruments and analyzers in developed countries. Furthermore, the increase
infectious Among the secondary effects due to the sudden globalization, accompanied by important migratory flows, there is the continuous development of infectious diseases which, especially in less than optimal health conditions, require both early diagnosis and adequate prevention and treatment. This health picture is one of the main factors that amplify the demand for immunological analyzers and compact consumer products in the diagnostic-health sector as it has been happening in recent months with the advent of the COVID-19 emergency.

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The industry in the sector is growing rapidly thanks to the introduction and constant adoption of automated and advanced techniques for laboratory instruments and analyzers in developed countries. Furthermore, the increase in infectious diseases and suboptimal clinical-health conditions require early diagnosis, and this is one of the main factors that increases the demand for immunological analyzers and compact consumer products in the healthcare sector. For this reason, the industry in the sector is responding quickly to the demand with the launch of innovative products such as the compact and portable Ichroma II from Boditech Med [3] and the Architect i1000SR Inc. from Abbott diagnostic [4] which is, among other things, an automated tool for immunological analyses based on the chemiluminescence principle. In this context, our design proposals will be able to obtain an excellent response since they go in the direction of the market, both in terms of development of the diagnostic system and in terms of portability and reduction of the overall dimensions of the system itself.

Key companies, such as Abbott Laboratories, bioMerieux, Inc. and Roche Diagnostics and some of the other leading players on the market including Becton Dickinson & Company; Diasorin S.p.A; Bio Rad Laboratories; and Siemens Healthcare GmbH, nowadays already supply optically-based immunoassays but the introduction and adoption of automated systems and innovative designs should intensify competition, changing the industrial framework in the forecast period, also giving new realities great opportunities for development.

In the recent years many papers deal with the possibilities to further integrate the microplates reader systems [5] and to give them the possibilities to better follow the evolution of the samples in therms of space and time [6].

In this work a set of innovative solutions, with respect to the standard solutions already on the market [7-9], have been employed and patented [10]. In our solution, the light source is provided by organic light emitting diodes (OLEDs) and Photonic Crystals (PCs) have been applied in order to select specific wavelengths to irradiate biological samples. Finally, organic photodiodes (OPDs) have been utilized to reveal and acquire the light passing through the sample.

In detail, a series of PCs have been used in order to limit the band of light extracted to the requirements of the systems on the market, which are very strict in terms of wavelengths (usually: 405 nm, 450 nm, 492 nm, 550 nm, 620 nm) and bandwidth (about 10nm) [7-9]. The use of photonic crystals can play a significant role in fostering and in reaching a higher level of integration for optical circuits by replacing the commonly used interference filters.

Therefore, the proposed photometric station adopts LEDs allowing the entire spectral band to be covered before the crystals select it and applies organic photodiodes in order to integrate the system as much as possible and provide further highly innovative developments in optical path terms and construction flexibility. Diseases and suboptimal clinical-health conditions require early diagnosis, and this is one of the main factors that increases the demand for immunological analyzers and compact consumer products in the healthcare sector. For this reason, the industry in the sector is responding quickly to the demand with the launch of innovative products such as the compact and portable Ichroma II from Boditech Med [3] and the Architect i1000SR Inc. from Abbott diagnostic [4] which is, among other things, an automated tool for immunological analyses based on the chemiluminescence principle. In this context, our design proposals will be able to obtain an excellent response since they go in the direction of the market, both in terms of development of the diagnostic system and in terms of portability and reduction of the overall dimensions of the system itself.

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Therefore, the proposed photometric station adopts LEDs allowing the entire spectral band to be covered before the crystals select it and applies organic photodiodes in order to integrate the system as much as possible and provide further highly innovative developments in optical path terms and construction flexibility.

2. Experimental

Recent studies have dealt with the coupling of LEDs and OLEDs to photonic crystals for several purposes [11-16]. This approach has shown countless potentials because the band-gap of the PCs can be tuned by changing the shape and/or the pitch of the reticle [17]. Moreover, the total internal reflection of transparent substrates can be exploited in the transport the light to specific locations and the application of PCs to select the light bandwidth with the spectral properties required by the analysis. Then, it is possible to select a narrow portion of the emission band of a large spectrum source, as the OLEDs usually are, making these devices suitable for this application.

Furthermore, the possibility of using OLEDs and PCs on the same substrate gives us the possibility of having a light source, of selecting the wavelengths and of minimizing the passage of luminous radiation into the air, eliminating various optical losses (Fig. 1). The development of the organic electronics platform gave us the possibilities to think to the use of the OPD as photodetectors considering a subsequent possible further development on flexible substrates.

2.1. Preparation of OLED sources

To ensure the correct bandwidth of emission wavelengths (from 405nm up to 620nm) and to demonstrate that with this system is possible to ensure full bandwidth coverage also by using a single light emitting source, two types of OLEDs have been prepared having white light emission and in the UV-blue range. High-performance OLEDs have been processed by applying active emissive layers prepared using phosphorescent materials. These materials are generally organometallic complexes having a heavy metal atom inside the molecules [18,19]. The structure of these molecules makes it possible to exploit all the excitons produced, both those in the singlet state and those in the triplet state making them potentially able to reach an internal quantum efficiency close to 100% [20]. In the following, it is possible to see the structure of the adopted OLEDs:

- UV-blue OLED (390nm-550nm): glass / ITO (200 nm) / PEDOT:PSS (40 nm) / NPD (35 nm) / CBP: Ir(Fppy)_3 / BCP (10 nm) / Alq3 (10 nm) / Ca/Al (20 nm / 80 nm);
- White OLED (420nm-700nm): glass / ITO (200 nm) / PEDOT:PSS (40 nm) / NPD (35 nm) / SimCP (5 nm) / SimCP:Ir(btp)_2(acac) 3% wt (10 nm) / SimCP (5 nm) / SimCP:Ir(ppy)_3 7% wt (25 nm) / BCP (9 nm) / Alq3 (10 nm) / Ca/Al (20 nm / 80 nm).

2.2. Preparation of Photonic crystals filters

To create the photonic crystals useful for the selection of the wavelengths, a positive photorefrist film (ZEP520A) was deposited by spin-coating on different glass/ITO substrates. The spinning conditions used, with which a thickness of about 200nm has been obtained, are 3000 rpm for 1 minute with an acceleration of 1000rpm. On the ZEP film, various photonic crystals with the structure and the steps shown in figure 2 have been structured with EBL technique. In the manufacturing phase, the substrates covered by the resist were exposed to the electronic beam of the EBL-RAITH 150 system. Through a special software, the electron beam is programmed to expose specific regions of the polymer with the previously designed nanopatterns. After being exposed to the electron beam, the samples under examination were subjected to the development procedure. In particular, the development of the positive resist ZEP520 was performed through a preliminary immersion for 90 s in Xylene, then 90 s in Methyl Isobutyl Ketone (MIBK): Isopropanol (IPA) 1:3 and finally 30 s in IPA.
Fig. 2: An image design of the hypothesized structure for the PC and a table related to the used names for the different PC pattern, the dimensions used for the lattice steps and the extraction wavelengths.

2.3. Preparation of OPD detectors

Photodiodes with inverted architecture have been made: glass/ITO/ZnO/PBDTTT-C:[70]PCBM/MoO$_3$/Ag [21]. In particular, the OPD prototype manufacturing layout can be divided into the following construction steps: definition of the frontal contact, with photolithography of the ITO for its selective removal; synthesis by sol-gel of ZnO and its deposition by spin-coating; preparation, realization and deposition of the active layer by spin-coating; deposition of the rear contact by high vacuum thermal evaporation.

3. Results

In this section we will show which architectures and geometries will be used for the devices (OLED and OPD) and photonic structures in order to guarantee the correct functioning of the photometric station with respect to the construction constraints initially hypothesized.

3.1. OLED sources

As already stated, to ensure the correct bandwidth of emission wavelengths (from 405nm up to 620nm) two types of OLEDs have been prepared. In figure 3 and figure 4 are shown the UV-blue and the White emission spectra for the two different OLEDs with an active area of 1 cm$^2$.

Fig. 3: Blue OLED emission spectrum at different supplied currents.

Fig. 4: White OLED emission spectra, acquired at various current intensities.

3.2. Photonic crystals filters

As mentioned before, for the in vitro analysis system, in our case, the use of five wavelengths has been envisaged (405, 450, 492, 550 and 620 nm) to be usually employed in spectrometric systems already on the market. For this reason, several simulations have been conducted on square-based photonic structures involving the selection of the aforementioned wavelengths. Figure 5 shows an image relating to the simulations carried out and which will be used to verify the goodness of our results on real structures. The resonance frequencies of the structures were calculated using a finite difference numerical method in the time domain (band solve tool, RSOFT software) and it is noted that by varying the step of the structures, from $a = 266$ nm to $a = 406$ nm, it is possible to obtain all the wavelengths required by the application. The extraction spectra, shown in figure 3, show how the geometries and chosen materials allow in the case of square-based geometry to obtain light extracted at wavelengths close to those required.

As can be seen in all cases, the spectrum of the experimental light emitted has a peak at a wavelength slightly lower than that obtained from the simulations and required for the development of the system. In particular, the relative variations calculated as $\varepsilon_r = [(\lambda_{\text{sim}} - \lambda_{\text{spec}}) / \lambda_{\text{sim}}]$ (where with $\lambda_{\text{sim}}$ we indicate the simulated extracted wavelength and with $\lambda_{\text{spec}}$ we indicate the same experimental parameter) are equal to about 1%. For a final device to be put on the market, this systematic error must be taken into account, probably due to the construction steps of the photonic crystals and the reticular pitch must be increased appropriately to eliminate this inconvenience.

The extraction spectra in figure 5 show how designed geometries and materials allow to obtain wavelengths and bandwidths (around 10 nm) close to those required.
Fig. 5: Simulated and experimental spectra of the light extracted from the selected PCs.

From the angular radiance extracted from the crystals it can be observed that all the square-based structures have a symmetrical emission, not isotropically diffused on the entire hemisphere (not Lambertian) but directional and limited in a vertical cone of about 30° overall. The angular radiances obtained for the photonic crystal structures, are summarized in figure 6.

![Angular radiances for square-based photonic structures.](image)

In figure 7 the trends of the peak wavelength extracted as the angle of view (θ = 0° means that the substrate is viewed perpendicularly) changes are shown. From the graph in figure 7, it can be observed that, for all the structures analyzed, as the extraction angle changes, there is a blue-shift of the peak wavelength with the maximum value measured at the angle of θ = 20°. This shift from the value of the wavelength emitted to 0° is in any case less than 15nm for all structures.

Fig. 7: Extracted peak wavelength vs view angle (θ).

3.3. OPD detectors

The photodiode must be sensitive to a broad spectrum including the five reference wavelengths. Then, a specific photoactive blend has been chosen: poly[(4,8-bis-(2-ethylhexyloxy)-benzol[1,2-b:4,5-b’]dithiophene)-2,6-diyl-polymer alt-(4-ethylhexanoyl)-thieno[3,4-b]thiophene)-2,6-diyl] (PBDTTT-C) and fullerene [6,6]-phenylC71butyric acid methyl ester ([70]PCBM) [21].

The photodiode has a dark current of 8.56E-9 A/cm² at 50mV of reverse bias while under light condition the photogenerated current is 16.0E-3 A/cm² in the same bias conditions (??). Furthermore, by varying the intensity of the incident light, the linearity of the photodiode current was verified for at least 2 OD, in accordance with the specific request, as shown in Figure 8a. In Figure 8b, the photodiode spectral response is reported and shows a good response between 400 and 650 nm as required by the application.
4. Discussion

The characterization of the full system (see also figure 1, but with one OLED source) has been performed using optical density filter to simulate the absorbance of different samples. Different organic light sources (blue or white) OLED have been coupled, from time to time, with PCs at 405 nm and 450 nm (blue light), and PCs at 492 nm, 550 nm and 620 nm (white light), and OPDs. In figure 9, it is possible to observe the OLED coupled with a photonic crystal working at 495 nm.

The OPD photocurrents are measured using a Keithley K6517A Electrometer and related to the used optical density filters.

The low values of the photodiode currents, especially for the OD2 filters make us understand that the optical paths need to be further improved, because even if we used a diffuser (barium sulphate, BaSO4) on the other face of the glass on which the OLED was built there were still too many optical losses (see figure 9). The losses increase also because the crystal and the OLED were not made, in this case, on the same substrate, furthermore, as can still be seen in figure 7, there are further optical losses also around the substrate on which the crystal is made.

In spite of it, evaluating all the data of Table 1, where reported the OD filters and the corresponding measured OPD voltage and photocurrents, it can be stated that our system follows all the specific requirements, including wavelengths and optical bands.

<table>
<thead>
<tr>
<th>OLED</th>
<th>PC (nm)</th>
<th>OD</th>
<th>OPD (I)</th>
<th>OPD (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>405</td>
<td>0</td>
<td>1,89E-08</td>
<td>4,63E-02</td>
</tr>
<tr>
<td>Blue</td>
<td>405</td>
<td>1</td>
<td>2,27E-09</td>
<td>2,77E-03</td>
</tr>
<tr>
<td>Blue</td>
<td>405</td>
<td>2</td>
<td>3,21E-10</td>
<td>4,33E-04</td>
</tr>
<tr>
<td>Blue</td>
<td>450</td>
<td>0</td>
<td>1,78E-08</td>
<td>4,81E-02</td>
</tr>
<tr>
<td>Blue</td>
<td>450</td>
<td>1</td>
<td>2,15E-09</td>
<td>2,71E-03</td>
</tr>
<tr>
<td>Blue</td>
<td>450</td>
<td>2</td>
<td>3,02E-10</td>
<td>4,20E-04</td>
</tr>
<tr>
<td>White</td>
<td>492</td>
<td>0</td>
<td>2,15E-08</td>
<td>5,80E-02</td>
</tr>
<tr>
<td>White</td>
<td>492</td>
<td>1</td>
<td>2,68E-09</td>
<td>3,40E-03</td>
</tr>
<tr>
<td>White</td>
<td>492</td>
<td>2</td>
<td>2,97E-10</td>
<td>4,13E-04</td>
</tr>
<tr>
<td>White</td>
<td>550</td>
<td>0</td>
<td>3,72E-08</td>
<td>8,23E-02</td>
</tr>
<tr>
<td>White</td>
<td>550</td>
<td>1</td>
<td>4,47E-09</td>
<td>5,54E-03</td>
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<tr>
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<td>2</td>
<td>5,21E-10</td>
<td>7,24E-04</td>
</tr>
<tr>
<td>White</td>
<td>620</td>
<td>0</td>
<td>3,35E-08</td>
<td>7,84E-02</td>
</tr>
<tr>
<td>White</td>
<td>620</td>
<td>1</td>
<td>4,02E-09</td>
<td>4,98E-03</td>
</tr>
<tr>
<td>White</td>
<td>620</td>
<td>2</td>
<td>5,02E-10</td>
<td>6,88E-04</td>
</tr>
</tbody>
</table>

The detection of the signal carried out through the use of an OPD showed the appropriate photoresponse, also because of a proper selection of the signal with a bandwidth of around 10 nm and of an acquisition range from 0 to 2 OD (optical density), as required. Furthermore, in figure 10 the OPD current data for the various OD filters, obtaining the same type of behavior already seen in the figure 8a without altering the behavior of the photodiode up to OD2 are reported, as further and last requirement strictly connected to the solutions already present on the market.
5. Conclusions

In conclusion, the proposed system solves the problem of using an interference filter for the selection of wavelengths. This is achieved by integrating the light source with a wavelength selector. Interestingly, it has been shown that eventually both the source and the wavelength selection could be realized on a single substrate. Finally, the proposed system addresses both the small size constraints for the equipment and the limits in the optical path, minimizing optical losses and avoiding possible measurement errors. Furthermore, it ensures greater applicability in complex systems with the possibility of creating a completely organic-based structure, also guaranteeing the possibility of making low-cost, flexible, and disposable chips for analysis.

6. Acknowledgements

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Figure 10: OPD photocurrent data vs OD filters for all the tested wavelengths.


[22] https://www.arduino.cc/
Non-Hermitian Photonics: From Plasmonics, and Metamaterials, to Topological and Quantum systems
Nonequilibrium dynamics and thermalization in open quantum many-body systems

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Abstract
I will present two distinct theoretical formalisms to analyze out-of-equilibrium open many-body dynamics with an arbitrary number of quantum jumps. First, I discuss propagation of correlations beyond the conventional bound known as the Lieb-Robinson bound in continuously monitored open quantum systems, originating from the nonorthogonality of non-Hermitian eigenstates. Second, I show that a generic nonintegrable many-body system subject to continuous observation thermalizes itself at a single-trajectory level. This finding provides a way to efficiently solve a many-body Lindblad master equation.

1. Introduction
The last two decades have witnessed remarkable developments in studies of many-body physics in an isolated, closed quantum system. Meanwhile, recent experimental advances have allowed one to measure and manipulate many-body systems at the single-quantum level, thus revolutionizing our approach to many-body physics. In particular, these developments point to a new research arena of open quantum many-body systems, where an interaction with an external observer and environment plays a major role.

From a broader perspective, recent studies on open systems described by non-Hermitian Hamiltonians in photonics and metamaterials have revealed their intriguing physical properties. However, the previous works mainly concerned the classical (one-body) aspects. Thus, many-body aspects of non-Hermitian systems, or more generally, nonunitary open quantum systems has remained largely unexplored. We aim to fill this gap and create a bridge between quantum many-body physics and nonunitary open systems, including non-Hermitian systems.

2. Results
2.1. Supersonic propagation of correlations
Generalizing the notion of full-counting statistics to open many-particle systems, we develop a theoretical formalism to analyze out-of-equilibrium dynamics under continuous observation with an arbitrary number of quantum jumps.

Figure 1: (a) Schematic illustration of an exactly solvable nonunitary open many-particle system. Half-filled spin-polarized fermions are trapped in an optical lattice and are subject to continuous observation, in which quantum jump corresponds to a loss of a single particle. (b) Energy dispersion of a non-Hermitian effective Hamiltonian associated with the model. At wavenumber $k = \pi$, two bands can coalesce and an exceptional point occurs around which the nonorthogonality becomes singularly strong. (c) Unconditional (left-most panel) and full-counting (other panels) equal-time correlations for different numbers $n$ of quantum jumps. White dashed lines represent the light cone associated with the Lieb-Robinson bound.

[1]. Specifically, we consider an open many-particle system and unravel its time evolution by introducing the density matrix conditioned on the number of quantum jumps being observed during a certain time interval. We apply our formalism to an exactly solvable model for fermionic systems and study its nonequilibrium dynamics under continuous observation, in which quantum jump corresponds to a loss of a single particle. We reveal the emergent unique features such as supersonic propagation of correlations beyond the Lieb-Robinson bound at the cost of probabilistic nature of quantum measurement (see Fig. 1). We identify the origin of these phenomena as the non-Hermiticity of the continuously monitored dynamics, which becomes most prominent at an exceptional point of an effective Hamiltonian.
In our solvable model, this singular point coincides with a spectrum transition point in the parity-time (PT) symmetric non-Hermitian Hamiltonian.

2.2. Thermalization

In the previous part, we have studied out-of-equilibrium dynamics in open many-particle systems under quantum measurement. Meanwhile, after such transient dynamics, it is natural to expect that an interacting many-body system will ultimately equilibrate. In this part, we would like to ask the question of whether or not statistical mechanics remains valid as a description of nonunitary open many-body systems [2]. Specifically, we consider the dynamics that is intrinsically nonunitary and the detailed balanced condition is violated because coupling to nonthermal environment permits general nonunitary processes such as continuous measurements and engineered dissipation. The primary goal of this part is to combine the idea of the eigenstate thermalization hypothesis (ETH) with quantum measurement theory to extend the framework of quantum thermalization to nonunitary open many-body systems coupled to generic external environments. The results are applicable not only to nonintegrable many-body systems under continuous observation, but also to dissipative Lindblad dynamics of generic many-body systems coupled to environments (that are not necessarily thermal) or under noisy unitary operations (see Fig. 2). Finally, time permitting, I will also discuss different subjects of non-Hermitian topological phenomena that can be realized in active matter [3, 4].

Figure 2: Comparison between the prediction from the matrix-vector-product ensemble (MVPE), which is based on a single quantum trajectory calculation (red solid line), and the Lindblad dynamics (black dashed curve). In nonintegrable open systems, the eigenstate thermalization hypothesis allows one to efficiently solve the open many-body Lindblad equation based on only a typical single quantum trajectory, but not by taking the full ensemble average over a large number of quantum trajectories.

Acknowledgement

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References

Hamiltonian and Liouvillian exceptional points in noisy non-Hermitian systems

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Abstract
We discuss the relation between Hamiltonian and Liouvillean exceptional points (EPs) in non-Hermitian systems with parametric noise. Conclusions for the performance of EP-based sensors are drawn.

1. Introduction
EPs of order $n$ (EPs) are spectral degeneracies where not only $n$ eigenvalues coalesce but also the corresponding eigenstates. These degeneracies have attracted lots of attention in the context of open quantum and wave systems not only because of the interesting, often counterintuitive, physics but also because of novel applications such as ultrasensitive sensors [1, 2, 3, 4]. One exploits the fact that when a non-Hermitian Hamiltonian $\hat{H}_0$ at an EP is subjected to a perturbation of strength $\varepsilon$, $\hat{H} = \hat{H}_0 + \varepsilon \hat{H}_1$, then the resulting energy splitting is generically proportional to $\varepsilon^{1/n}$. For small $\varepsilon$ this gives considerably larger splittings than in the case of degeneracies in Hermitian Hamiltonians where the splitting is linear [1]. Certain aspects of (quantum) noise on the performance of such sensors have been discussed in Refs. [5, 6, 7, 8, 9].

Here, we discuss the impact of a fluctuating system Hamiltonian $\hat{H}_0$ on the performance of EP-based sensors. In contrast to Ref. [9] we adapt a transparent Lindblad-type formalism which allows us to study the resolvability of the energy splitting and the dynamical stability of the sensor in a unified manner by comparing the behavior of Hamiltonian and Liouvillian EPs.

2. The Lindblad-type master equation
We consider a fluctuating EP by adding $\xi(t)\hat{H}_{\text{noise}}$ to the system Hamiltonian $\hat{H}_0$ with real-valued $\xi(t)$ describing a white Gaussian noise with variance $\gamma$. Using Itô calculus we derive for the density operator $\hat{\rho}$ an inhomogeneous Lindblad-type master equation

$$\frac{d\hat{\rho}}{dt} = \mathcal{L}\hat{\rho} + \hat{\mathcal{P}}(\omega)$$

(2)

with the superoperator $\mathcal{L}$

$$\mathcal{L}\hat{\rho} = -i\left(\hat{H}_{\text{eff}}\hat{\rho} - \hat{\rho}\hat{H}_{\text{eff}}^\dag\right) + \gamma\hat{H}_{\text{noise}}\hat{\rho}\hat{H}_{\text{noise}}^\dag,$$

(3)

the effective Hamiltonian

$$\hat{H}_{\text{eff}} = \hat{H} - \frac{i}{2}\hat{H}_{\text{noise}}^2,$$

(4)

and the pump operator describing a coherent pump $e^{-i\omega t}\hat{P}$ with frequency $\omega$

$$\hat{P}(\omega) = -i\left(|\hat{P}\rangle\langle\hat{P}|\hat{G}(\omega) - \hat{G}(\omega)|\hat{P}\rangle\langle\hat{P}|\right)$$

(5)

with the Green’s operator $\hat{G}(\omega) = \left(\omega\mathbb{1} - \hat{H}_{\text{eff}}\right)^{-1}$; $\mathbb{1}$ is the identity operator. From Eqs. (2) and (5) it can be deduced that the measurable spectral properties of the system are determined by $\hat{H}_{\text{eff}}$.

The superoperator $\mathcal{L}$ in Eqs. (2)-(3) determines the stability of the system. This can be best seen in Liouville space, where $\hat{\rho}$ and $\hat{P}$ are represented as $n^2$-dimensional vectors and $\mathcal{L}$ is represented as a $n^2 \times n^2$ matrix (the Liouvillian), where $n$ is the dimension of Hilbert space. The stability of the system can be analyzed in terms of the eigenvalues $\lambda_i$ of $\mathcal{L}$. A stationary state $\hat{\rho}$ is in general only possible if all $\text{Re} \lambda_i \leq 0$.

3. Hamiltonian and Liouvillian EPs
We consider first an effective Hamiltonian $\hat{H}_{\text{eff}}$ without noise ($\gamma = 0$) and without perturbation ($\varepsilon = 0$) at an EP, which in the following is called an Hamiltonian EP (HEP). We prove that the corresponding Liouvillian EP (LEP) is of higher order, namely of order $2n - 1$.

The typical scenario for nonzero noise and perturbation is illustrated in Fig. 1. When the noise is switched on ($\gamma > 0$) the HEP is not destroyed and even its position in parameter space is not changed provided that $[\hat{H}_0, \hat{H}_{\text{noise}}^2] = 0$, a condition that is valid for typical realistic examples. In contrast, the Liouvillian is no longer at an LEP. Its eigenvalues split proportional to $\gamma^{1/(2n-1)}$. This has implications on the dynamical stability of the sensor. Consider a situation where the eigenvalues of $\mathcal{L}$ at the LEP are close to the imaginary axis. A splitting proportional to $\gamma^{1/(2n-1)}$ is parametrically large for small noise strength $\gamma$ and at least one of the roots of $\gamma^{1/(2n-1)}$ has a positive real part, so the corresponding eigenvalue may cross the imaginary axis leading to an instability; see also Ref. [9].

The instability can be removed by a uniform damping of the sensor, i.e., by adding $-\kappa\mathbb{1}$ to the system Hamiltonian $\hat{H}_0$, with the rate $\kappa$ above the critical rate $\kappa_c =$
Figure 1: Sketch of the complex spectrum of a $2 \times 2$ effective Hamiltonian $\hat{H}_{\text{eff}}$ (a) and the corresponding $4 \times 4$ Liouvillian $L$ (b). The green square marks an HEP and a LEP for the case without noise ($\gamma = 0$) and without perturbation ($\varepsilon = 0$). With increasing noise the HEP stays to be an EP but the eigenvalue moves in the complex plane (red plus symbol). In contrast, the LEP is lifted by the noise and the eigenvalues split proportional to $\gamma^{1/3}$ (red plus symbols). Increasing the perturbation strength gives an energy splitting of $\hat{H}_{\text{eff}}$ proportional to $\varepsilon^{1/2}$ (blue circles). The shaded yellow area marks the region of instability.

Re $\lambda_1/2$ with $\lambda_1$ being the eigenvalue of $L$ with the largest real part. Unfortunately, this reduces the resolvability since the linewidths broaden significantly.

We conclude that for EP-based sensors operating at or close to the real energy axis, as for instance in the case of parity-time symmetric systems, even small noise can indirectly, via the necessary stabilization, spoil the resolvability.

References


Localization and universality in non-Hermitian many-body systems

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Abstract

We show that novel and rich physics concerning localization and universality appears in non-Hermitian quantum many-body systems. As a first topic, we analyze non-Hermitian systems with asymmetric hopping in the presence of interaction and disorder. We demonstrate that a novel real-complex transition occurs upon many-body localization. As a second topic, we discuss universality classes of spectral statistics in non-Hermitian random matrices. We find two new universality classes characterized by transposition symmetry, which is distinct from time-reversal symmetry.

1. Introduction

Recent research on isolated quantum many-body systems has revealed two distinct phases distinguished by their dynamics and spectral statistics. One is an ergodic phase whose spectral statistics show random-matrix-type universality, and the other is a many-body localized (MBL) phase, where thermalization is prohibited owing to strong disorder. So far, however, the MBL and random-matrix-type universality have not been sufficiently understood in dissipative quantum many-body systems. We here present that novel and rich physics concerning localization and universality appears in non-Hermitian many-body systems, which have been utilized in diverse scientific disciplines from open quantum systems to biology.

2. Non-Hermitian many-body localization

We first discuss non-Hermitian MBL and its consequence to the reality of the spectrum [1].

2.1. Model

We consider hard-core bosons with asymmetric hoppings on a one-dimensional lattice as follows:

\[
\hat{H} = \sum_{i=1}^{L} \left[ -J \left( e^{-\beta} \hat{b}_i^\dagger \hat{b}_{i+1} + e^{\beta} \hat{b}_{i+1}^\dagger \hat{b}_{i} \right) + U \hat{n}_i \hat{n}_{i+1} + h_i \hat{n}_i \right],
\]

where \( \hat{b}_i \) is the annihilation operator of the hardcore boson, \( \hat{n}_i = \hat{b}_i^\dagger \hat{b}_i \), and the potential \( h_i \) is chosen randomly from \([-h,b]\) depending on the site \( i \). Importantly, this model respects time-reversal symmetry.

2.2. Real-complex transition

We numerically demonstrate a novel phase transition concerning the reality of the eigenvalues of \( \hat{H} \). It is shown that almost all eigenvalues become complex (resp. real) below (resp. above) some critical point. Indeed, if we define

\[
f_{\text{Im}} = \frac{\text{# of eigenvalues with a nonzero imaginary part}}{\text{# of total eigenvalues}},
\]

it shows a critical transition at \( h = h_c^R \) (complex phase) and \( f_{\text{Im}} \rightarrow 0 \) for \( h > h_c^R \) (real phase) in the thermodynamic limit, respectively. Note that this real-complex transition occurs at many-body level in the thermodynamic limit, in contrast with the conventional PT transition.

We find that this transition affects the non-Hermitian many-body dynamics. Below the transition point, the energy is emitted to or absorbed from the environment, which means that the dynamics is unstable. On the other hand, above the critical point, the energy is almost conserved, which indicates that the real phase is dynamically stable.

2.3. Many-body localization

The model exhibits another phase transition, i.e., the MBL. While it is nontrivial how to characterize MBL in non-Hermitian systems, we show that some known machinery to characterize MBL in isolated systems can be generalized to the non-Hermitian regime.

We first consider the level-spacing distribution of (unfolded) eigenenergies. In the Hermitian case, the level-spacing distribution on the real axis exhibits the Hermitian random-matrix-type distribution in the delocalized phase (\( h < h_{c}^{\text{MBL}} \)) and the Poisson distribution for the MBL phase (\( h > h_{c}^{\text{MBL}} \)). By generalizing this to the non-Hermitian case, we show that the level-spacing distribution on the complex plane exhibits the non-Hermitian random-matrix-type distribution, e.g., Ginibre distribution, in the delocalized phase (\( h < h_{c}^{\text{MBL}} \)) and that the (two-dimensional) Poisson distribution for the MBL phase (\( h > h_{c}^{\text{MBL}} \)). We secondly consider the entanglement entropy of energy eigenstates, and find the transition from the volume...
law to the area law as we increase the disorder, in a manner similar to isolated systems.

We also argue that two different transition points, \( h_{c}^{L} \) and \( h_{c}^{MBL} \), coincide in the thermodynamic limit in our asymmetric-hopping model. This argument is supported by the time-reversal symmetry and the stability argument of eigenstates and eigenvalues under non-Hermitian perturbation, which connects MBL and the reality of eigenvalues.

3. Universality classes of non-Hermitian random matrices

We next discuss universality classes of non-Hermitian random matrices [2]. Universality means that some spectral statistics, such as the level-spacing distributions, are described by those of the Gaussian random matrices irrespective of the detail of the matrix elements.

In Hermitian matrices, universal statistics can be classified by time-reversal symmetry (TRS): three distinct universal level-spacing distributions appear depending on three different symmetry classes A (with no TRS), AI (with TRS whose square equals to +1), and AII (with TRS whose square equals to −1).

However, we encounter a different situation for non-Hermitian random matrices with TRS. Indeed, matrices in non-Hermitian classes A, AI, and AII introduced by Ginibre lead to only a single universality class in stark contrast with the Hermitian case.

We solve this “paradox” by noting different symmetry classes called classes AI† and AII†, which respect transposition symmetry. Note that the transposition symmetry is distinct from TRS. Indeed, real matrices \((H = H^\dagger)\) in class A differ from the symmetric but complex matrices \((H = H^T)\) in the non-Hermitian case.

We numerically demonstrate that three distinct universal level-spacing distributions appear for classes A, AI†, and AII† as in the Hermitian case, instead of the Ginibre’s classes A, AI, and AII. This is because transposition symmetry can alter interactions between nearby eigenvalues, which is not possible for the other possible symmetries. Therefore, we argue that only the three universality classes with transposition symmetry exist among possible 38 types of non-Hermitian symmetry classes for level-spacing distributions.

Finally, we demonstrate that our newly found universality classes manifest themselves in open quantum many-body systems described by a Lindblad master equation. This clearly illustrates that our universality classes can be applied to physical systems as well.

4. Conclusion

We have shown that a real-complex transition occurs at non-Hermitian MBL with time-reversal symmetry and profoundly affects the dynamical stability of interacting systems with asymmetric hopping. We have also found new universality classes of the level-spacing distributions distinct from the Ginibre’s exclusively for symmetry classes with transposition symmetry. We believe that these works pave the way for understanding dynamics, chaos, and thermalization of dissipative (especially non-Hermitian) many-body systems.

Acknowledgement

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References


Ultrathin Acoustic Parity-Time Symmetric Metasurface Cloak

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Abstract

Invisibility or unhearability cloaks have been made possible by using metamaterials enabling light or sound to flow around obstacle without the trace of reflections or shadows. Metamaterials are known for being flexible building units that can mimic a host of unusual and extreme material responses, which are essential when engineering artificial material properties to realize a coordinate transforming cloak. Bending and stretching the coordinate grid in space require stringent material parameters; therefore, small inaccuracies and inevitable material losses become sources for unwanted scattering that are decremental to the desired effect. These obstacles further limit the possibility of achieving a robust concealment of sizeable objects from either radar or sonar detection. By using an elaborate arrangement of gain and lossy acoustic media respecting parity-time symmetry, we built a one-way unhearability cloak able to hide objects seven times larger than the acoustic wavelength. Generally speaking, our approach has no limits in terms of working frequency, shape, or size, specifically though we demonstrate how, in principle, an object of the size of a human can be hidden from audible sound.

References

Nonlinear spectral singularities and tunable laser with 2D material coating

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Abstract

We investigate the application of nonlinear spectral singularity in a nonlinear non-Hermitian optical system consisting of an infinite planar slab that is coated with a two-dimensional (2D) material in arbitrary transverse electric TE and transverse magnetic TM modes. The nonlinear spectral singularity condition provides a computational scheme for studying the laser output intensity for a slab of gain material in the presence of a weak Kerr nonlinearity. Here, we explore the effects of placing the slab between Graphene and 2D Weyl semimetal sheets. We show that the 2D material introduces additional physical parameters for tuning the output intensity of the laser.

1. Introduction

Spectral singularities are specific points of a continuous spectrum of complex scattering potentials where the transmission and reflection amplitudes diverge. This mathematical concept was initially introduced by mathematicians and has recently paved its way in physics. Ref. [1] provides a simple review of the mathematical structure of spectral singularities and their application. Optics can provide a productive research field where spectral singularity can be realized. For instance, Ref. [2] studies the effect of nonlinearity in the lasing condition of an infinite planar slab in the presence of weak Kerr nonlinearity. The main consequence of this study is the following expression for laser output intensity ($I$).

$$I = \frac{g - g_0}{\sqrt{\sigma}} \hat{I}, \quad (1)$$

where $g$ is the gain coefficient, $g_0$ is a threshold gain coefficient, $\sigma$ is a Kerr coefficient and $\hat{I}$ is a real function which is called the intensity factor and depends on the geometry and physical parameters of the system. Eq. (1) shows that by satisfying the nonlinear spectral singularity condition, lasing can occur whenever its gain coefficient $g$ exceeds the threshold gain $g_0$.

For oblique transverse electric (TE) and magnetic (TM) modes of an infinite planar slab of homogenous optically active material, Ref. [3] investigates spectral singularities and applies them to determine the threshold gain coefficient $g^E/\sqrt{N_1}$. In the presence of Kerr nonlinearity, Ref. [4] explores the existence of a nonlinear spectral singularity in the TE and TM modes of a mirrorless slab of gain materials and gives an explicit analytic expression for the laser output intensity. The main prediction of this study is that for TM modes, the lasing is forbidden for incident waves whose emission angle is larger than Brewster’s angle.

An interesting question that we address here is what happens if we place an infinite planar slab between two thin layers. Recently, Refs. [5, 6] apply the transfer matrix method to study $PT$-symmetric coherent perfect absorbers that are coated with two-dimensional (2D) materials. In this presentation, we review our recent numeric results of the behavior of the intensity slope associated with all relevant physical parameters for a slab with Graphene or Weyl semimetal coatings.

References


Instability of nonreciprocal non-Hermitian media

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Abstract

I develop a general response theory for non-conserving optical, mechanical or acoustic media in which Hermiticity is broken due to nonreciprocal effects. I show that these media undergo an instability phase transition when they display the non-Hermitian skin effect. This makes these media ideally suited as sensors and amplifiers.

1. Introduction

Nonreciprocal non-Hermitian media have gained a lot of interest due to the skin effect, in which right and left eigenmodes becomes localized at opposite edge of a system. Whilst this effect is well understood on mathematical grounds [1], its physical ramifications have not been widely explored. Here I develop a general response theory of such systems when they are excited by an external drive, and show that the response diverges in the large-system-size limit exactly when the skin effect occurs [2]. Thereby, the well-understood mathematical phase transition to the skin effect coincides with a physical phase transition that dramatically changes the stability of the system.

2. Results and discussion

For concreteness, consider a general non-linear medium with discretized degrees of freedom \( x \) subject to an external harmonic of amplitude \( y \),

\[
\ddot{x} + \gamma \dot{x} + Mx + y \cos(\omega t) = 0. \tag{1}
\]

Here, \( M \neq M^T \) for a nonreciprocal medium, and admits a spectral decomposition \( M = U \Omega^2 U^{-1} \) where \( \Omega \) contains the normal-mode frequencies, and \( U^{-1} \neq U^\dagger \) if the system is non-Hermitian. The term \( \gamma \) signifies the additional possibility of damping, and also serves to regularize expressions.

The key of this study is to explore the significance of these effects for the response function

\[
G = \text{Re}(U \frac{e^{-i\omega t}}{\omega^2 + i\gamma \omega - \Omega^2} U^{-1}). \tag{2}
\]

There are two key observations:

a) Close to resonance, the total power spectrum

\[
P_{\text{tot}} \approx \frac{K_n}{(\omega^2 - \Omega_n^2)^2 + \omega^2 \gamma^2} \tag{3}
\]

contains the Petermann factor

\[
K_n = (U^\dagger U)_{nn}(U^{-1}U^{-\dagger})_{nn} \tag{4}
\]

known from quantum-optical noise theory [3].

b) This Petermann factor diverges in large systems when the left and right eigenmodes of a resonance are localized at opposite sides of a system, as it occurs in the non-Hermitian skin effects.

I further illustrate these findings concretely in the context of a recent ground-breaking experiments on nonreciprocal robotic mechanical metamaterials, which displays the skin effect for a topological zero mode [4].

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References


Emergent $P\mathcal{T}$ symmetry and quantum fluctuations in a double-quantum-dot circuit QED set-up

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Abstract

Open classical and quantum systems with effective parity-time ($P\mathcal{T}$) symmetry have shown tremendous promise for advances in lasers, sensing, and non-reciprocal devices. However, the microscopic origin of such effective, non-Hermitian models is not well understood. In this work, by microscopically modelling a double-quantum-dot-circuit QED set-up that is realizable in state-of-the-art experiments, we show that a non-Hermitian Hamiltonian emerges naturally, which can be controllably tuned to observe both $P\mathcal{T}$-transition, as well as the effect of quantum fluctuations.

1. The set-up

The schematic diagram of the set-up is given in Fig. 1. The main parts of the set-up consist of the DQD and the two cavities. These are described by the following Hamiltonians:

$$
\hat{H}_{DQD} = \frac{\varepsilon}{2}(\hat{c}_1^{\dagger}\hat{c}_1 - \hat{c}_2^{\dagger}\hat{c}_2) + t_c(\hat{c}_1^{\dagger}\hat{c}_2 + \hat{c}_2^{\dagger}\hat{c}_1) + V\hat{c}_1^{\dagger}\hat{c}_1\hat{c}_2^{\dagger}\hat{c}_2,
$$

$$
\hat{H}_C = \omega_0(\hat{b}_1^{\dagger}\hat{b}_1 + \hat{b}_2^{\dagger}\hat{b}_2) + \lambda(\hat{b}_1^{\dagger}\hat{b}_2 + \hat{b}_2^{\dagger}\hat{b}_1),
$$

$$
\hat{H}_{DQD-C} = g_0\Theta(t)(\hat{c}_1^{\dagger}\hat{c}_1 - \hat{c}_2^{\dagger}\hat{c}_2)(\hat{b}_1^{\dagger} + \hat{b}_1),
$$

where $\Theta(t)$ is the Heaviside function. Here, $\hat{c}_{1,2}$ denote fermionic creation operators for sites 1 and 2 that model the DQD, $\varepsilon$ is the energy difference between the two sites, $t_c$ is the hopping amplitude between the two sites, and $V > 0$ denotes the capacitive charging energy between the two sites. $\hat{b}_{1,2}$ represent the bosonic creation operators for the two cavities, each with frequency $\omega_0$, that are coupled via a number-conserving hopping process with amplitude $\lambda$. Closely following the experimental set-ups, the DQD is dipole-coupled to the (first) cavity it is in with strength $g_0$ when the cavity is switched on at time $t = 0$. Thus, Eq. (1) captures the microscopic model of the DQD and the two cavities.

Each of the three main components is connected to multiple baths. All baths are modelled by Hamiltonians quadratic in bosonic or fermionic creation and annihilation operators. Each cavity is coupled to its own bosonic bath at inverse temperature $\beta$, with $\beta\omega_0 \gg 1$. The presence of these baths lead to a cavity decay rate of $\kappa_1$ ($\kappa_2$) for the first (second) cavity. Each site of the DQD is coupled to its own fermionic lead. The lead coupled to the first (second) site has inverse temperature $\beta$ and chemical potential $\mu_1$ ($\mu_2$). The strength of coupling to both leads is taken to be same and denoted by $\Gamma$. The entire set-up is realizable in state-of-the-art experiments with DQD coupled to circuit-QED cavities. However, to model experimental set-up consistently, we also have to consider that the DQD is dipole-coupled to a phononic bath in the substrate on which it is located [1].

We look at the parameter regime that ensures a resonant DQD, i.e. $\omega_0 = \omega_q$; a weak cavity-DQD coupling, i.e. $g_0/\bar{\eta}$ photons $\ll \Gamma$ ($\bar{\eta}$ photons is the average number of photons in the cavity coupled to the DQD), and

$$
\frac{\omega_q/2}{2} < -\mu_2, \mu_1 < V, \quad \kappa_1, \kappa_2, \lambda < \Gamma < \omega_0.
$$

In this parameter regime, the it can be shown that, for $\varepsilon > 0$, the DQD will be population inverted in the steady state in the absence of the cavities. The DQD thus acts as a controllable gain medium [2].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The set-up consists of two cavities connected to each other, with the left cavity having a double-quantum-dot out-of-equilibrium. The double-quantum-dot is configured to give a gain to the left cavity. If the gain is same as the loss of the right cavity, the bosonic system of the cavities have an effective $P\mathcal{T}$ symmetric dynamics.}
\end{figure}
2. The effective $\mathcal{P}\mathcal{T}$ symmetry

After integrating out the fermionic part and the bosonic baths, we have the effective equations of motion for the bosonic system,

$$\frac{d}{dt} \begin{pmatrix} \hat{b}_1 \\ \hat{b}_2 \end{pmatrix} \approx \mathbf{H}_{\text{eff}} \begin{pmatrix} \hat{b}_1 \\ \hat{b}_2 \end{pmatrix} + \begin{pmatrix} \tilde{\xi}_A \\ 0 \end{pmatrix}. \tag{3}$$

The $2 \times 2$ non-Hermitian Hamiltonian is given by

$$\mathbf{H}_{\text{eff}} = \begin{bmatrix} \omega_0 - i\kappa_1 + i\Gamma\delta & \lambda (1 - \delta) \\ \lambda (1 - \delta) & \omega_0 - i\kappa_2 \end{bmatrix}, \tag{4}$$

where $\delta = 2g^2\Delta N_{ss}/T^2 \ll 1$ by the choice of our parameters and $\Delta N_{ss} = \langle \hat{N}_1 \rangle_{ss} - \langle \hat{N}_2 \rangle_{ss}$ is the steady-state population inversion in the DQD in the absence of cavities. Here $\langle \hat{N}_1 \rangle_{ss}, \langle \hat{N}_2 \rangle_{ss}$ is the population of the higher (lower) energy state of the DQD in steady state in absence of the cavity. The time-dependent quantum noise operator $\hat{\xi}_A(t)$, resulting from the DQD gain, has almost zero mean value, $\langle \hat{\xi}_A(t) \rangle \approx 0$, and a Lorenzian power spectrum for the variance, i.e.

$$\langle \hat{\xi}_A^2(t)\hat{\xi}_A(t') \rangle \approx g^2 \langle \hat{N}_1 \rangle_{ss} \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \frac{2\Gamma e^{i\omega(t-t')}}{(\omega - \omega_0)^2 + \Gamma^2}. \tag{5}$$

In all of the equations above, the expectation value represents quantum statistical average, i.e. $\langle O \rangle = \text{Tr}(\rho_{\text{tot}} O)$ where $\rho_{\text{tot}}$ is the density matrix for the initial state of the whole set-up. The effective Hamiltonian in Eq. 4 can be tuned to observe both active and passive $\mathcal{P}\mathcal{T}$ transition just by tuning the parameters $\epsilon$ and $t_0$ of the DQD and by tuning the parameter $\lambda$ of the cavities. As can be easily seen from Eq. 3, the effect of the various phases will be observed in the dynamics of the complex quadratures $\langle \hat{b}_e(t) \rangle$ ($\ell = 1, 2$). However, our complete microscopic derivation has lead to occurrence of the additional noise term $\hat{\xi}_A(t)$, in consistency with fluctuation-dissipation theorem. The presence of $\hat{\xi}_A(t)$ lets us study the effect of quantum fluctuations on the dynamics of $\mathcal{P}\mathcal{T}$-symmetric and $\mathcal{P}\mathcal{T}$-broken phases.

As an example, here, in Fig. 2, we show the effect of quantum fluctuations on the active $\mathcal{P}\mathcal{T}$-symmetric phase where the eigenvalues of $\mathbf{H}_{\text{eff}}$ are real. The dynamics is shown starting from a state where the cavity with the DQD (gain cavity) is in a coherent state with the other cavity (loss cavity) is empty. The amplitudes of the complex quadratures show periodic oscillations characteristic of the $\mathcal{P}\mathcal{T}$-symmetric phase. However, the quantum fluctuations of the quadratures, given by $\langle \hat{b}_e(t) \rangle - |\langle \hat{b}_l(t) \rangle|^2$, show linear growth superimposed with oscillations. Similar behavior is seen in the photon current $I(t) = \text{Im}(\langle \hat{b}_2^2(t)\hat{b}_1(t) \rangle)$, where $\text{Im}(\cdot)$ refers to imaginary part.

3. Conclusions and further work

The set-up of two coupled cavities with a voltage biased DQD in one of them provides a perfect test bed for exploring effective $\mathcal{P}\mathcal{T}$-symmetry in the quantum regime, and explore the effect of quantum fluctuations. While not discussed in the above summary, we have also explored the effect of passive $\mathcal{P}\mathcal{T}$-transition in input-output experiments. Further, we have been able to show that as a consequence of the passive $\mathcal{P}\mathcal{T}$-transition, loss induced lasing can be observed in the set-up.

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References


Stability optimization of random networks with added non-Hermitian nodes from a parity-time symmetry perspective

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Abstract

A network being described by a real symmetric coupling matrix between its elements, we look at the addition of gain and loss elements that are coupled to the network, in such a way as to maximize the so-called unbroken phase of the parity-time symmetry approach now familiar in optics: we minimize imaginary parts of eigenvalues. We explore with Fourier tool how coupling should be arranged and attempt to find rules similar to those established for “stability-optimized-circuits” in the context of neural networks.

1. Networks, stability and Parity-time symmetry

Random matrices and stability of networks are two tightly connected topics since the pioneering work of R.E. May [1] in 1972 on the stability of ecological system (somehow circumventing the explicit Lotka-Volterra prey-predator solving). The argument was that the eigenvalue of a random matrix tends to localize in a circle of complex plane, and that the radius of this circle should be less then unity, relating thus matrix sparsity and matrix coefficients variance in a simple formula. Network are of course much more ubiquitous in all the science of the last decades, e.g. neural networks or biochemical networks, whereas optical networks with some kind of randomness (behavior close to the chaos threshold) have been used for instance to implement reservoir computing.

On the other hand, parity-time symmetry (PTS) contends as a central paradigm the manifestation of a real spectrum (the absence of imaginary part of eigenvalues) in spite of the presence of (balanced) imaginary parts on a diagonal of an Hamiltonian’s matrix [2].

To apply PTS to networks is interesting because the unbroken phase (real spectrum) corresponds to a stability condition. This is not at all a mundane issue. For instance, a description of actual neural networks of primates (those of motion control) was recently proposed based on “SOC”, stability-optimized circuits [3], with the aim of describing how inhibitory and excitatory (~amplifying) neurons are organized to fire their signals to muscles in a complex sequence that is crucial for high performance motion.

In this contribution, we attempt to knit in a different way the issue of “stability optimization”, a minimization of imaginary parts of a network containing individual, and PTS. We start from a random matrix and study coupling conditions that minimize a figure of merit associated to imaginary parts of eigenvalues, starting with a Fourier approach of how the coupling (=network edges) is distributed over the preexisting nodes (=vertices) of the network. We give in this contribution only the first steps to give a feeling of the approach that we will later develop in more depth.

2. State-of-the-art

The stability of networks with amplifying elements inside is a topic that might have been hidden by various factors. In the important area of biochemical networks, for instance, there are few widely accepted instances of bona fide “amplification” of a quantity (an analyte concentration) by itself, except maybe Ca2+ ions in neurons. But an ensemble of two or three species can form a network with complex eigenvalues, much as one learns that complex numbers emerge from real matrices or quaternion numbers from Pauli matrices.

In neural networks, the work of Hennequin et al. [3] made an interesting breakthrough for real neural networks, as said above, gain being associated to excitatory neurons and loss to inhibitory ones. The mathematical approach [4] used to align eigenvalues in a suitable (stable) region of complex plane (so in the same spirit as the unbroken phase of PTS) makes use of Lyapunov matrices, and is not very tractable for physicists with a PTS background. That is why we propose to start another approach here, more in line with the PTS background.

3. Random matrix and Fourier approach

3.1. Matrix build up

We start from a real random symmetric N×N matrix M representing the strength of coupling between nodes (in the spirit of [1]), \(<M_i^2>=1/2\sqrt{N}\), and typically N≈100 for tests. The eigenvalues of M are distributed according to the well-known Wigner semi-circle law (of unit radius) in terms of histogram representation.

We now add two extra rows and columns and define an augmented matrix Q of size (N+2)x(N+2) such that the N×N truncation of Q is M. We also set non-Hermitian nodes \(Q_{1,N+1}=+i\gamma\) and \(Q_{N+2,N+2}=-i\gamma\), and leave \(Q_{N+1,N+1}=0\).

We now add two extra rows and columns and define an augmented matrix Q of size (N+2)x(N+2) such that the N×N truncation of Q is M. We also set non-Hermitian nodes \(Q_{1,N+1}=+i\gamma\) and \(Q_{N+2,N+2}=-i\gamma\), and leave \(Q_{N+1,N+1}=0\).
To couple the gain-loss “template” thus added to the pre-existing network of \( M \), we make a Fourier scan: We introduce the formulation \( Q_{N+1,m} = \cos(qm)/2N \) or \( Q_{N+1,m} = \sin(qm)/2 \), for \( 1 \leq m \leq N \), with \( q \) a Fourier wavevector that we vary, spanning \( 0 \leq q \leq 2\pi(N-1)/N \) in \( N \) steps of \( 2\pi/N \). In this way, we explore which Fourier profile of the coupling gives the better PTS unbroken behavior (“in phase” for \( \cos(qm) \) or “in quadrature” for \( \sin(qm) \)). As for the \( N+2 \) column \( Q_{N+2,m} \), it is chosen identical to \( Q_{N+1,m} \), and to respect symmetry (hermiticity) the two rows \( Q_{m,N+1} \) and \( Q_{m,N+2} \) are also identical. We have thus built \( Q = Q(q,\gamma) \).

### 3.2. Analysis of first result

We then scan \( \gamma \) (the gain-loss parameter) as classically done for PTS, and we explore if there is an unbroken range for the eigenvalues and how large it is depending on \( q \). The results show no correlation between “cos” and “sin” responses, as is logical for such a random matrix starting point. We thus find that a synthetic way to present the result is to build the following “cos” or “sin” versions of a simple PTS figure merit \( F_{\text{sin}} \) or \( F_{\text{cos}} \).

\[
F_{\text{sin},\gamma}(q,\gamma) = \max \left( |\text{Im}(\lambda_q)| \right),
\]

where \( \lambda_q \) are the eigenvalues of \( Q(q,\gamma) \), and to plot \( F_{\text{sin}}(q,\gamma) \) as a function of \( F_{\text{cos}}(q,\gamma) \) as a set of \( N \) \( \gamma \)-parametrized curves (one for each \( q \)). In this way, we observe the typical range of unbroken regime visually, as can be seen on a numerical example in Fig.1 (with \( N=40 \) only), indexing curves by the integer \( Nq/2\pi \) \( (0 \leq Nq/2\pi \leq N-1) \). The best candidates for large unbroken regime are found here at \( Nq/2\pi=34 \) (along “sin” axis) and 35 along “cos” axis (both are circled, limit of unbroken regime circled as well on each axis).

![Figure 1: Plots of \( F_{\text{sin}}(q,\gamma) \) vs. \( F_{\text{cos}}(q,\gamma) \); each curve is a \( \gamma \)-scan. Integer wavevector indices \( (Nq/2\pi) \) are indicated. The symbol size decreases linearly with \( q \) so curves with small symbols near the origin correspond to large unbroken regimes of both \( F_{\text{sin}}(q,\gamma) \) and \( F_{\text{cos}}(q,\gamma) \), while curves starting far from the origin correspond to a large unbroken regime only for one of the two \( F \)’s.](image)

To also add the information on the range, we plot \( F \)’s with increasing marker size for increasing gain/loss \( \gamma \). An examination of the region near the origin shows that the only small \( \gamma \)’s are observed there, so the possibility that \( F_{\text{sin}} \) and \( F_{\text{cos}} \) both remain 0 up to large \( \gamma \), although highly desirable, seems very unlikely.

We observe a variety of phenomena, and no obviously privileged frequency \( q \). Importantly enough, a majority of cases show an unbroken symmetry behavior, which is a good basis to further gain stability.

### 4. Perspective and conclusion

From these first steps, the rest of the strategy has to be designed to build up a large ensemble with “balanced” gain loss and a large unbroken domain for the overall behavior. This would correspond to a “stabilized” network, less prone to divergence in spite of the presence of amplifying nodes. Indeed, a neural network can be though as an architecture (the nondiagonal elements) combined with an “engine” (the non-Hermitian gain or loss nodes), and we want the engine to work unconditionally, without “crashing” the system.

Firstly, we have to see if we can take advantage of combination of the best Fourier cases to extend the range of unbroken cases in our basic cases of 2 added elements or in simple similar ones.

Secondly, the general strategy would then be to continue adding “active” nodes to an initial small cluster (\( N, N+2, N+4, \ldots \)) maybe not even balancing gain and loss exactly (nature does not...), and to test how much we manage to build a complex network with stabilized properties. We could then compare the result to the strategy used in [3]. There are certainly weaknesses in this simplified view, but we believe that the topic of growth of complex systems has not received a specific attention from the point of view of granting its stability, and that the PTS tools is an interesting approach to address this problem. The Fourier approach, on the other hand, is more generic, and could be replaced by other “localization” methods more related to identified network topologies (“small-world” for instance).

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### References


Correlations of indistinguishable photons in quantum walks under broken PT-symmetry

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Abstract
We experimentally study the correlations of indistinguishable photons in a one-dimensional Parity-Time (PT) symmetric quantum walk. Introducing a symmetric loss distribution in a homogeneous waveguide system gives rise to PT-symmetry, which drastically alters the correlations of indistinguishable photons, giving rise to e.g. correlations similar to distinguishable classical particles in a random walk.

1. Introduction
Since the first discussion of Parity-Time (PT) symmetry by Bender & Boettcher in 1998 [1], numerous PT-symmetric effects and systems have been studied in photonics [2]. A wide range of experimental research covers investigations from topological bound states under PT symmetry [3] over transport mechanisms [4] to lasing [5] and has been continued to quantum interference lately [6].

Our approach to study dynamics in a PT-symmetric lattice utilizes quantum random walks, a powerful tool for investigations of complex systems that is applied for instance in search algorithms or quantum computing.

2. Quantum walks in the PT-symmetric lattice
PT symmetric potentials can be employed in optics by implementing a symmetric real part of the refractive index and an antisymmetric imaginary part (gain/loss) [7]. However, in quantum systems any gain would introduce thermal noise, necessarily changing the propagating quantum state [8]. To avoid this effect, we deploy an entirely passive system, where the desired non-Hermitian dynamics can be separated from a global loss factor acting on the system. [9]

Optical waveguide systems have proven to be a versatile platform to realize such potentials. In turn, we implement PT-symmetry in a homogenous waveguide lattice that can be described by the Hamiltonian

$$H = \sum_{n=1}^{N} \left( \beta - i h \frac{\gamma_n}{2} \right) \hat{a}_n^\dagger \hat{a}_n + \sum_{m=n \pm 1} \kappa \hat{a}_m^\dagger \hat{a}_n$$  \hspace{1cm} (1)

with $\hat{a}_m^\dagger \hat{a}_n$ describing the creation/annihilation of a photon in site $n$ of a lattice with equal propagation constant $\beta$, alternating loss $\gamma_n$ and homogenous nearest neighbour coupling $\kappa$. In such a lattice, PT-symmetry is always broken [3]. Under the assumption of Markovian loss, the dynamics of quantum states in such a system can be straightforward obtained from a quantum Langevin equation [10].

To explore the influence of PT-symmetry on the correlations of indistinguishable photons, we employ a lattice of equidistant waveguides, where every second waveguide exhibits loss, while every other lattice site is neutral without gain or loss. The corresponding waveguide structure is depicted in Figure 1. Subsequently, pairs of indistinguishable photons are launched into the waveguide structure in different configurations, and the coincidences at the output are retrieved using avalanche photo detectors.

Figure 1: The experimental setup consists of a homogenous lattice of evanescently coupled waveguides with a hopping constant of $\kappa = 0.5 \text{ cm}^{-1}$ and in the PT-symmetric case a loss of $\gamma = 0.99 \text{ cm}^{-1}$ in every second (odd) waveguide, that is implemented via bending loss.

The results for the correlation matrices after the propagation through the PT-symmetric lattice with the aforementioned experimental parameters are shown in Figure 2 for an input state of two indistinguishable photons being launched a) into two neighboring waveguides with loss and no loss and respectively into nearest-next sites exhibiting b) both loss or c) both no loss. For comparison, also the corresponding Hermitian lattice (with equal parameters, but without loss) is illustrated.
Especially the last case, where both photons are launched into lossless waveguides, the PT-symmetric coincidence matrix deviates strongly from the Hermitian case. Here, the loss in the lattice gives rise to dynamics that resemble the random walk of completely classical and distinguishable particles e.g. on a Galton board.

3. Conclusions

We describe the influence of a PT-symmetric potential on a continuous quantum walk of indistinguishable photon pairs. This influence results intriguing dynamics, leading to coincidence dynamics that resemble the random walk of classical, uncorrelated particles.

References


Encircling exceptional points as a non-Hermitian extension of rapid adiabatic passage

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Abstract

Coherent transfer of population between different energy levels is a key task in quantum mechanical applications with rapid adiabatic passage (RAP) being one of the most prominent protocols. By reframing the underlying process in the domain of non-Hermitian physics through adding a variable amount of loss we theoretically and experimentally disclose a fundamental connection between the symmetric state flip of RAP and the asymmetric state transfer when encircling an exceptional point (EP) [1, 2, 3].

1. Introduction

In principle, the transfer of excitations between two energy levels of a Hermitian system is a straightforward task that can be implemented by switching off a resonant coupling that induces Rabi oscillations between these two levels at exactly the right moment. It is much harder, however, to devise efficient transfer schemes with an inherent robustness against imperfections of the coupling mechanism with RAP being among the most popular ones. For RAP the external drive must be turned on and off adiabatically such that the system remains in an instantaneous eigenstate. This process coherently transfers the population from one energy level to the other.

Now, when we appropriately add losses to the same RAP scheme, the Hermitian degeneracy splits into a pair of EPs where one of the two EPs is then located inside of the control cycle. This small adaptation effectively turns a scheme for RAP into a protocol for EP-encircling. While RAP symmetrically switches the population of the uncoupled eigenstates even if the parameter cycle is performed in reverse, encircling an EP is known to create an asymmetric state transfer: independent of the initial configuration the final population distribution solely depends on the sense in which the encircling loop is traversed.

Here we demonstrate how applying a suitable loss contrast to an existing RAP scheme acts as a switch between symmetric (RAP) and asymmetric (EP-encircling) population transfer.

2. Non-Hermitian extension of RAP

We start by analyzing a typical protocol for RAP based on a two-level system described by the Hamiltonian

\[ H = \begin{pmatrix} -\Delta - i\gamma & \Omega \\ \Omega & \Delta + i\gamma \end{pmatrix}, \]

(1)

where \( \gamma \) describes the variable loss contrast. The Hamiltonian in Eq. (1) generally has complex eigenvalues \( \lambda_{\pm} = \sqrt{(\Delta + i\gamma)^2 + \Omega^2} \). The dynamical evolution of the level amplitudes \( (c_1(t), c_2(t))^T = \psi(t) \) is governed by the Schrödinger equation \( \frac{d}{dt}\psi(t) = -iH(t)\psi(t) \) where the detuning \( \Delta(t) \) and the coupling \( \Omega(t) \) dynamically follow a semicircular control path,

\[ \Omega(t) = r \sin(\pi t/T), \]

\[ \Delta(t) = \pm r \cos(\pi t/T) + \rho, \]

(2)

depicted in Fig. 1(a), where \( r \) is the radius of the circle, \( \rho \) is its horizontal offset and \( T \) is the period of the loop. Figure 1(c) then shows the dynamic evolution of the state vector when projected onto the eigenspectrum of the Hamiltonian. If the semicircular path is traversed adiabatically (solid green/violet arrow) and fictitiously closed along the straight section passing the DP (dashed green/violet arrows), \( \Omega = 0 \), such that the final state is spanned in the same eigenbasis as the initial configuration, the symmetric state switch immediately becomes apparent. Naturally every experimentally realized RAP protocol will be subject to small amount of losses, which inevitably split the Hermitian degeneracy into a pair of EPs located at \( \Omega = \pm \gamma \) [see Fig. 1(b)]. However, as long as the loss contrast is negligible the dynamical evolution of the state vector still shows the symmetric switch [depicted in Fig. 1(d)] even when an EP is encircled. This is true regardless of the direction in which the cycle is performed.

3. Critical loss contrast

A key feature of the dynamics in non-Hermitian systems is the breakdown of the adiabatic theorem, even in the limit of arbitrarily slow evolution, that can lead to sudden non-adiabatic transitions between the instantaneous eigenstates.
Here we have demonstrated the intimate connection between RAP in Hermitian systems and the asymmetric state transfer related to encircling an EP. For every asymmetric RAP protocol ($\rho \neq 0$) there is a critical loss contrast $\gamma_c$ such that the state transfer becomes asymmetric with respect to the encircling direction. Adequately positioning a thin absorber in a microwave waveguide can therefore act as a switch to interchange between symmetric and asymmetric population transfer.

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Figure 1: Clockwise RAP scheme using a semicircular loop $A \rightarrow B$ that is fictitiously closed along the straight path $B \rightarrow A$ crossing the diabolical point (DP) in the Hermitian case (a) and encircling the exceptional point (EP) in the non-Hermitian case (b). In (c,d) the dynamical evolution of the state vector is projected onto the real part of the eigenspectrum where violet/green arrows show the state evolution starting in the first/second level. The red (gain) and blue (loss) regions in (d) correspond to $\Im(\lambda_{\pm}) > 0$ and $\Im(\lambda_{\pm}) < 0$, respectively.

Surprisingly, this does not implicate that the final state is always the least dissipative one. Instead, when we increase the loss contrast $\gamma$ up to a certain critical value

$$\gamma_c \simeq \frac{r}{T|\rho|} \ln \left( \frac{T(r - |\rho|)^2}{\pi r} \right),$$

the state transfer suddenly becomes chiral. It can be seen from Eq. (3) that the critical loss contrast diverges if the horizontal offset $\rho$ goes to 0. In fact, the asymmetry between the clockwise and the counterclockwise propagation direction induced by $\rho$ is the root cause for the chirality in the state transfer. In Fig. 2(a) we show a map of the state transfer property (symmetric or asymmetric) for each configuration $\{\rho, \gamma\}$. The dashed blue line marks the critical loss contrast from Eq. (3). After we have established the fundamental connection between RAP and the chiral state transfer we devised a two-mode microwave waveguide with undulating boundaries that shows RAP in the transmitted left-to-right ($T_{ji}$) and right-to-left ($T_{ji}'$) scattering states [see Fig. 2(b)]: the intermode transmission intensities $T_{12} = T_{21}'$ and $T_{21} = T_{12}'$ are much larger than the intramode ones $T_{11} = T_{11}'$ and $T_{22} = T_{22}'$. To switch from RAP to the chiral state conversion we place a thin absorber in the same waveguide. Now the measured intensities satisfy $T_{21} \gg T_{22}, T_{11} \gg T_{12}$ and $T_{12}' \gg T_{22}', T_{11}' \gg T_{21}'$, which is a hallmark of the chiral state transfer [depicted in Fig. 2(c)].

Conclusions: Here we have demonstrated the intimate connection between RAP in Hermitian systems and the asymmetric state transfer related to encircling an EP. For every
On the connection between parity-time symmetry and time-variant wave media

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Abstract
Parity-time symmetry can allow non-Hermitian Hamiltonians to exhibit real eigenvalues. This interesting condition of symmetries has enabled numerous studies in the fields of quantum mechanics and optics. Such theoretical and experimental studies involve a combination of material gain and loss. In this talk, we connect the phenomena that are related to parity-time symmetry with the wave phenomena that are related to temporal changes of the wave parameters of the medium, by introducing a time-transitioning matrix.

1. Introduction

The possibility to control and manipulate waves by exploiting tailored distributions of gain and loss is key in many modern devices, leading to unique radiative and scattering properties. A laser, which is probably the most representative case of a non-Hermitian system, consists of a spatial distribution of gain in an open resonant cavity. A certain intensity threshold represents the maximum gain, which can be balanced by the leakage losses provoked by radiation to the external space. At threshold, the system radiates an amplified monochromatic signal (lasing). In mathematical terminology, the threshold value characterizes the solution of the linear wave equation in terms of its stability. When the laser is operated below this value, the solution is stable. Conversely, when the laser is operated above this value, the linear solution is unstable, and the laser output eventually saturates due to nonlinear effects.

In recent years it was found [1] that non-Hermitian Hamiltonians under parity-time symmetry can exhibit real eigenvalues, meaning that a symmetric distribution of gain and loss can result, under specific circumstances, to propagating modes with real frequency. This scientific observation has expanded the research in modern laser theory, as Maxwell’s equations can be mapped directly to a Hamiltonian formulation, as for optical beams under the paraxial approximation [2]. At the same time, there has been a renewed interest by the research community centered in the wave phenomena exhibited by time-varying media. In this talk we will discuss the non-trivial and intriguing connections between the wave phenomena under time-variant wave media and the parity-time operator.

2. Time-transitioning state matrix formulation

Let us assume a ferroelectric medium with no-dispersion, which is pumped by an external time-varying agent. Its resulting Maxwell’s equations enforce the electric displacement and magnetic induction fields to be continuous under any time variation of the medium. In the case of a homogeneous but effectively time-variant medium the resulting second order differential equations are separable [3]. Waves under such a medium conserve their wavenumber but their frequency is altered. As the $k$-component of the field remains unchanged the analysis comes down in the modelling of the time-dependent part of the wave solutions:

$$\zeta(r,t) = \xi_0 \cos \left( k \cdot r - \frac{1}{2\varepsilon} \left( \frac{4e\kappa^2 - \sigma\mu}{\mu} \right) t \right) \exp \left( -\frac{\sigma t}{2\varepsilon} \right).$$

It is possible to show that we can map the problem in the determination of the coefficients $C(t) = [C_1, C_2]^T$ (which determine the positive and negative propagation direction) of the two time-dependent wave solutions $T_1, T_2$ (the mapping is done for the electric displacement and magnetic induction fields). Then, we can define the time-transitioning matrix $H(t)$ as:

$$C(t) = H(t-t')C(t').$$

This time-transitioning matrix defines the evolution of the modes as the medium is dynamically changing and can thus be considered as a time-evolution operator, equivalent to a Hamiltonian (although the interpretation of the eigenvalues and eigenmodes is different as we find out later) [4]. If the medium at $t = t$ changes permittivity and permeability abruptly (from $\varepsilon_1, \mu_1$ to $\varepsilon_2, \mu_2$), it can be shown that for any later observation time $t'$ ($t < t'$), $\det(H(t')) = 1$ (which is a consequence of the lossless character of the ferroelectric). Moreover the eigenvalues of $H(t')$ are $\lambda_\pm = b \pm \sqrt{b^2 - 1}$ and the eigenmodes are:

$$C_\pm = [a, \lambda_\pm + c]^T,$$

where
\[ b(\tau, \tau') = \cos \left( \frac{k_+}{\sqrt{\mu_+}} \right) \cos \left( \frac{k_{\tau-\tau'}}{\sqrt{\mu_{\tau-\tau'}}} \right) - \sin \left( \frac{k_+}{\sqrt{\mu_+}} \right) \sin \left( \frac{k_{\tau-\tau'}}{\sqrt{\mu_{\tau-\tau'}}} \right), \]

\[ a = -\frac{i(\epsilon_1 \mu_+ - \epsilon_0 \mu_{\tau-\tau'})}{2\sqrt{\mu_+ \mu_{\tau-\tau'}}} e^{-\frac{k_{\tau-\tau'}}{2\sqrt{\mu_{\tau-\tau'}}}} \sin \left( \frac{k_{\tau-\tau'}}{\sqrt{\mu_{\tau-\tau'}}} \right) \]

and

\[ c = -e^{-\frac{k_{\tau-\tau'}}{2\sqrt{\mu_{\tau-\tau'}}}} \cos \left( \frac{k_{\tau-\tau'}}{\sqrt{\mu_{\tau-\tau'}}} \right) + \frac{i(\epsilon_1 \mu_+ - \epsilon_0 \mu_{\tau-\tau'})}{2\sqrt{\mu_+ \mu_{\tau-\tau'}}} e^{-\frac{k_{\tau-\tau'}}{2\sqrt{\mu_{\tau-\tau'}}}} \sin \left( \frac{k_{\tau-\tau'}}{\sqrt{\mu_{\tau-\tau'}}} \right). \]

3. Time-reversal and parity operators

If we apply the time-reversal operator \( T \) then the corresponding time-transitioning matrix has to resemble the physical phenomena as time travels backwards, hence the time-reversal relation is:

\[ \left( TH^{-1}(\tau')T \right)(TC) = \lambda^{-1}(TC). \]

If \( \tau' = 2\tau \) then the time-transitioning matrix has interchanged eigenvalues and eigenmodes with \( H(\tau') \). If we apply the parity operator \( P \) it is straightforward to show that for real \( \lambda \), the system is unchanged, whereas for complex \( \lambda \), the eigenvalues and eigenmodes are interchanged. Finally, we can conclude that if we apply the \( PT \) operator, a double interchange of the eigenvalues and the eigenmodes occurs, which is the definition of a parity-time symmetric system.

4. Exceptional points

The eigenvalues satisfy the condition: \( \lambda_+ \lambda_- = 1 \). The system supports two propagating modes when \( |\lambda| < 1 \) (as both eigenvalues are complex and unitary) and one evanescent and one parametrically amplifying for \( |\lambda| > 1 \) (as one is lower and the other higher than unity). The special transition case: \( |\lambda| = 1 \) is associated with exceptional points since the eigenvalues and the eigenmodes collide: \( \lambda_+ = \lambda_- = \pm 1 \) and \( C_+ = C_- \). The associated phase diagram is highly complex as it depends on all the variables and the time-observation \( k, \epsilon_1, \mu_+, \epsilon_2, \mu_-, \tau, \tau' \).

5. Conclusions

In this talk we introduced an appropriate mathematical modeling that connects the notion of parity-time symmetry with wave phenomena induced by time variations of the wave medium, and discuss the consequences in terms of devices that control amplification based on parametric amplification.

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References


Topological bulk lasing mode in non-Hermitian kagome lattices

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Abstract

Due its robustness against disorders, topological edge modes have been used to enhance the performances of lasers. Recently, it has been shown that the quality of topological lasers can be further improved using novel topological phases in one-dimensional non-Hermitian photonic topological insulators. Here, we demonstrate topologically protected mode extended over the bulk of a two-dimensional kagome lattice with rhombus geometry by introducing an imaginary gauge field. This show the possibility to achieve a phase-locked broad-area topological lasers in two-dimensional lattices.

1. Introduction

Photonic topological insulators (PTIs) [1] are characterised by the presence of topologically protected edge modes at the interface between two topologically distinct materials. These topological modes are robust against structural defect and environmental fluctuations and can therefore feature uni-directional propagation insensitive to defect.

Recently, PTIs have been studied in a non-Hermitian context by engaging these edge states in lasing regime with optical nonlinearity, distribution of gain and loss or non-reciprocal couplings. For example, the non-Hermitian one-dimensional Su-Schrieffer-Heeger (SSH) model has been proposed to generate edge states and topological lasing devices [2, 3, 4]. From a cavity made of topologically distinct PTIs, the uni-directionality of the topologically protected edge mode has been used to enhance the lasing efficiency [5, 6, 7]. Moreover, broad-area topological laser has been proposed by using extended topological mode in a two-dimensional hexagonal cavity [8] based solely on the parity symmetry of the mode at the Γ-point or by using imaginary gauge field in a one-dimensional $PT$-symmetric SSH lattice to delocalise the zero-energy edge mode over the bulk [9].

In this paper, we delocalise the topologically protected mode over a two-dimensional kagome lattice with a rhombus geometry by using an imaginary gauge field.

2. Results

In kagome lattices, one can have access to an analytical expression of the edge states by using the formalism developed in Ref. [10]. Figure 1 shows the geometry of the lattice in terms of stacked I and J lattices to form a kagome lattice with open boundary only in the $e_2$-direction and terminated by the I lattices. The couplings between sites are different for intra-unit cell ($t_1$) or inter-unit cell ($t_2$). The I lattice is composed of two-sites unit cell and, because of the intra- and inter-unit cell coupling strengths, is equivalent to the SSH model. The J lattice is composed of a single site (B) in its unit cell. Thanks to the frustrated configuration between the I and J lattices, one can see the stacked lattices I and J as being equivalent of the SSH model. From this pseudo-one-dimensional formalism, natural edge modes of the kagome lattice, with penetration depth $\xi$, arise as being the eigenstate $\psi_j$ of the Hamiltonian $H_I$ in the I lattice with energy $E_i$ and having wave amplitudes on the B sites because of destructive interferences.

Since $H_I = H_{SSH}$, for a finite geometry in the $e_1$-direction terminated with broken unit cell, i.e. terminated with the A sites, the zero-energy mode of the SSH model is guaranteed by its chiral symmetry $\Gamma$: $\Gamma H_{SSH} \Gamma = -H_{SSH}$. This zero-energy mode has a penetration depth $\xi_0 = \ln(\frac{t_2}{t_1})$ along the (A,C)-bulk, and have a fixed π phase shift between adjacent A sites. Applying an imaginary gauge field $h$ in the $e_1$-direction (see $e^{ih}$ in Fig. 1), one can delocalise the zero-energy mode over the one-dimensional (A,C)-bulk of the SSH chain with a suitable value of $h = \frac{1}{2} \ln \left( \frac{t_2}{t_1} \right)$ [9].
The imaginary gauge field does not affect the spectrum the SSH model since a gauge transformation of the wave function reduces to the original SSH model equations. Therefore, the gap remains open and the zero-energy mode remains protected against local perturbation preserving the chiral symmetry (on-site energy, coupling strength, etc). However, the localisation properties depend of the perturbation on the coupling strength $t_1$ and $t_2$ since $h$ depends explicitly on it.

Looking at the zero-energy eigenstate for the I lattices, $E_i = 0$, one obtain $\xi_i = \ln\left(\frac{t_2}{t_1}\right)$. Repeating the same procedure for the SSH-like I/J stacked lattices, one can delocalise the zero-energy edge mode over the (I,J)-bulk. This is achieved with an imaginary gauge field in the $e_2$-direction (see $e^{h'}$ in Fig. 1): $h' = \frac{1}{2} \ln \left(\frac{2}{t_1}\right)$.

By introducing an imaginary gauge field potential $A \propto (-ih, -ih')$, one can delocalise the topological mode over the two-dimensional bulk of the kagome lattice with rhombus geometry. This is therefore a topological bulk mode. Figure 2 shows the field profile of the topological bulk zero mode with $h = h' = \frac{1}{2} \ln \left(\frac{2}{t_1}\right)$.

Using semiconductor ring resonator with dynamical gain and a $PT$-like symmetric configuration of gain ($g$) and loss ($-g$), it can be demonstrated the possibility to get stable phase-locked broad-area topological lasers in two-dimensional lattices [11].

## 3. Conclusions

In summary, we have shown a recipe to get a topologically protected bulk mode in a kagome lattice by using an imaginary gauge field. As a consequence of the chiral symmetry of the SSH lattice, the obtained topological bulk mode is robust to local perturbations that preserve the symmetry. Using a configuration of gain an loss similar to a $PT$-symmetric system, we have shown the possibility to achieve phases-locked broad-area topological lasers in two-dimensional kagome lattices.

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Quantum interference with bianisotropic metasurface

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Abstract
We investigate how quantum interference can be controlled by using bianisotropic metasurfaces. By considering a bianisotropic metasurface with material loss from metal, we numerically demonstrate an asymmetric control of quantum interference with an origin from an exceptional point of the metasurface in the classical regime.

1. Introduction
Metasurfaces have been extensively investigated with great performance in modulating light, such as beam steering [1]. One particular interest is to control scattering parameters on-demand, allowing the study of exceptional point in the case of lossy metasurfaces [2,3]. For example, unidirectional zero reflection (UZR) occurs at exceptional point [4]. On the other hand, recent interest in adopting metasurfaces in the quantum optics arises, including metasurface-enabled quantum state construction [5] and entangled photon source [6]. In quantum regime, different from classical case, we have quantum two-photon interference [7], which is the central operation in quantum information processing. Our work focuses on how the quantum interference is related to the phenomenon at the exceptional point. In particular, we investigate a bianisotropic metasurface and show that two-photon quantum interference can be controlled in an asymmetric manner.

2. Asymmetric reflection from a lossy bianisotropic metasurface
Here, we start from designing a metasurface to give rise to an exceptional point with UZR and consider quantum state transformation through such a metasurface. We will be able to see how the asymmetric response in a classical metasurface can be inherited to the quantum optical level. A unit cell of the metasurface consists of two Au bars of two different sizes in the vertical y-direction respectively on front and back surface normal to z (inset of Fig. 1). The incident plane wave comes from either the forward (+z) or the backward (−z) direction. The forward (backward) reflection amplitude is shown in the green (orange) curve while the point of UZR occurs at around 341 THz in Fig. 1: \( r_0 = 0 \). It means a coalesce of the two eigenvalues and eigenvectors of the \( 2 \times 2 \) scattering matrix \( S = \{ \{ t, r_b \}, \{ r_f, t \} \} \), i.e., an exceptional point of \( S \). The scattering parameters exhibit resonance from around 300 to 420 THz. In the design procedure, we also make the reflection amplitude \( |r_f| \) as high as possible so to make a larger effect in the later quantum interference.

3. Asymmetric quantum interference
To evaluate the quantum interference of the bianisotropic metasurface, we adopt the Lindblad master equation [8,9] in writing the Liouvillian super operator \( \mathcal{L} \) as

\[ \mathcal{L} \rho = -i[\hat{R}_{\text{eff}} \rho - \rho \hat{R}_{\text{eff}}^\dagger] + 2 \sum_{j,k} \gamma_{jk} \hat{a}_k \rho \hat{a}_j^\dagger, \] (1)

which can be related to the scattering matrix through

\[ \hat{R}_{\text{eff}} = \sum_{j,k} (i \ln S)_{jk} \hat{a}_j^\dagger \hat{a}_k, \] (2)

while the second term in Eq. (1) is the quantum jump term derived from the non-Hermitian part of scattering matrix \( S \), which incorporates the loss of the metasurface. Then, the density matrix is calculated according to \( \rho_{\text{out}} = e^{\mathcal{L} \tau} \rho_{\text{in}} \). Suppose we use \( 10 ((01)) \) to represent single-photon state in the forward (backward) channel of the metasurface, and \( 11 \) to represent two-photon state with one photon in each of the forward and backward channels. We can calculate the
detection probability of output state $|\alpha\rangle$ as $P_Q(|\alpha\rangle) = \langle \alpha | \rho_{out} | \alpha \rangle$. When we have a $|11\rangle$ input, Fig. 2 shows the detection probability for $|10\rangle$ output state (blue color), i.e., an output photon in the forward direction, and the detection probability for $|01\rangle$ output state (orange color) respectively. The system output is therefore very asymmetric in the forward and backward directions as a large difference between the blue and the orange curves from around 300 to 420 THz near the resonance of the metasurface. Such an asymmetric response is inherited from the classical UZR effect, but their magnitudes cannot be explained quantitatively from their classical correspondence, which are now plotted $P_C(|10\rangle)$ and $P_C(|01\rangle)$ in the same figure (green and red curves). We will also discuss the condition in generating destructive quantum interference around the UZR frequency to get zero detection probability in a similar manner to HOM effect.

Figure 2: Different output probabilities from $|11\rangle$ input at different frequency calculated in quantum (with subscript Q) and classical (with subscript C) method.

4. Conclusions

We have investigated a bianisotropic metasurface with unidirectional zero reflection at exceptional point and numerically demonstrated the asymmetric quantum interference effect induced by the bianisotropic metasurface with loss considered. This study provides an opportunity to tailor the quantum interference when designing metasurfaces.

Acknowledgements

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References

Quantum correlations in PT-symmetric systems

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Abstract

We study the dynamics of correlations in a paradigmatic setup to observe PT-symmetric physics: a pair of coupled oscillators, one subject to a gain one to a loss. Quantum correlations (QCs) are created, despite the system being driven only incoherently, and can survive indefinitely. We link PT-symmetry breaking to the long-time behavior of QCs, which display different scalings in the PT-broken/unbroken phase and at the exceptional point (EP). The EP in particular stands out as the most classical configuration.
Exotic atom-photon interactions in a non-Hermitian photonic lattice

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Abstract
We study emission properties and dipole-dipole interactions for a set of quantum emitters (atoms) coupled to a photonic lattice with engineered losses which exhibits the non-Hermitian skin effect. A number of exotic quantum optics effects occur such as loss-induced chiral emission, exactly localized metastable dressed states, chiral photon-mediated atom-atom interactions. At a lattice exceptional point, the effective couplings between the emitters are exactly non-reciprocal and short-range.

References
Non-Hermitian media with global and local unidirectionality: theory and applications

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Abstract

Structured media provide the momentum compensation for the scattering of waves. It is well-known that nano-scale modulations of the refractive index may lead to a temporal and spatial control over light propagation. Yet, also engineering the gain and loss profile uncovers analogous shaping effects. However, only the interplay between both the refractive index and gain and loss modulations introduces unidirectionality in light management. Thus, non-Hermitian optics has become one of the most fertile grounds in optics. A generalized Hilbert transform allows tailoring the two quadratures of the complex permittivity to design periodic or disordered non-Hermitian media, holding either global, i.e. homogeneous or local, i.e. non-homogeneous unidirectionality following arbitrary vector fields to tailor the flow of light. In this paper we provide a review of a modified Hilbert transform leading to non-Hermitian potentials for the control of the scattering of waves and smart light propagation with various applications. Moreover, the method allows restricting the permittivity within realistic values rendering it suitable for applications.

1. Introduction

Losses have always been regarded as a drawback for applications and physicist have therefore looked towards the modelling of perfect Hermitian systems. As an example, in photonics, the search for artificial media for the control of light transport was born with perfect non-absorbing photonic crystals. Nano-scale periodic modulations of the refractive index modify the spatial and temporal dispersions enabling optical properties among which maybe the most celebrated applications are spectral forbidden bands and spatial beam shaping effects as are filtering and flat lensing. Most of such effects relay on the momentum compensation provided by the structure in the scattering of light. Also, in non-periodic distributions, the structure may lead to light scattering accounted by an analogous mechanism. More recently, attention was also paid to non-Hermitian systems where only gain and losses were modulated on the wavelength scale leading to similar spatial effects such as light diffusion, negative refraction or self-collimation [1]. However, the most interesting situation arises from the interplay of real and imaginary out of phase modulations of the permittivity. Non-Hermitian potentials with degeneracies (exceptional points), whilst being not new [2], allows for a novel class of synthetic materials with unprecedented properties also attracting high interest in photonics for its relatively achievable fabrication [3].

2. Local and global modified Hilbert transform

The proposed method is based on a judicious filtering of the scattering potential (permittivity) at the reciprocal wavevector domain. Scattering of waves from/to particular directions and for particular frequency ranges is suppressed through a generalized Hilbert transform relating the two quadratures of the complex permittivity of an object, which is less demanding than the conventional spatial Kramers-Kronig relations providing full unidirectional scattering cancellation, see Fig. 1a. Following an iterative chain of generalized Hilbert transforms, allows restricting the required modification of the complex refractive index within realistic limits (for example avoiding gain or loss) [4]. In turn, a local Hilbert transform allows to design non-Hermitian potentials generating arbitrary vector fields of directionality, with desired shapes and topologies; by modifying background potentials (being either regular or random as in Fig. 1b, extended or localized) [5]. Such directionality fields, may form a channel or create sinks for probe fields, see Figs. 1c and 1d. Moreover, a flexible mechanism for dynamical shaping and precise control over
probe and realizable with a limited collection of realistic materials has recently been proposed [6]. This mechanism can also be optimized to efficiently produce non-Hermitian potentials from any arbitrarily given real (or imaginary) permittivity distribution for the desired frequency selective and broadband asymmetric reflectivity [7].

The generalized Hilbert transform is a feasible invisibility approach, suppressing the scattering of waves from/to particular directions and for particular frequency ranges, on demand, as in Fig. 2a. It was demonstrated that a global transform yields optical transparency for any arbitrarily shaped object. The design principle was verified by experimental observations at the microwave regime and full-wave numerical calculations [4]. In turn, the local Hilbert transform may find direct applications in the regularization of the emission of semiconductor light sources. A non-Hermitian potential in the form of a sink, as in Fig. 1c, may find direct applications in the regularization of the emission of VCSELS [8], as shown in Fig. 2b. A radially dephased periodic refractive index and gain-loss modulations accumulate the generated light from the entire active layer and concentrate it around the structure axis to emit narrow, bright beams. The unstable spatiotemporal dynamics, shown on the left image of Fig. 2b, is spatially regularized and stabilized due to asymmetric inward radial coupling between transverse wave vectors. The effect occurs for particular phase differences of the radial refractive index and gain-loss modulations as depicted in the central image of Fig. 2b where the main concentration is obtained close to 90°. Also, a non-Hermitian configuration controls and stabilize the spatiotemporal dynamics of edge emitting lasers. A pump modulation, with a mirror-symmetric central axis which induces in-phase gain and refractive index modulations due to the Henry factor. Both modulations may be, in turn, spatially dephased by an appropriate index profile to yield to a local PT symmetry within the modified BAS laser. Such local PT-symmetry potential induces an inward mode coupling, accumulating the light generated from the entire active layer at the central symmetry axis, which ensures spatial regularization and temporal stability., a central symmetry axis enhances and localizes the generated light [9], see Figs. 1d and 2c. An analogous scheme may be extended the mirror-symmetric non-Hermitian coupling to an array of EEL (diode bar) to achieve asymmetric coupling not within a single laser but between neighboring lasers. The non-Hermitian EEL bar scheme takes advantage of the symmetry coupling breaking, achieving a localized and central output that could directly connect to optical fibers. [10]

Figure 1: Scattering mechanism in wavevector domain. Total cancellation of the backwards scattering by 2D Kramers-Kronig relations in space and generalized Hilbert transform kernel for scattering cancellation on demand. b) Local Hilbert transform in 1D generating a sink in a random media. c)/d) Local Hilbert transform in 1D generating a sink and a channel.

3. Applications

The generalization of 1D Hilbert transform to a 2D space, as shown in Fig. 1c, may find direct applications in the regularization of the radiation from a VCSEL [8] or a dielectric S-shaped object, and broadband invisibility from the modified object by the global Hilbert transform with a symmetric kernel. The insets show the permittivity, real and imaginary parts.

Figure 2: Scattering cancellation applications in linear and nonlinear media. a) Scattering from a dielectric S-shaped object, and broadband invisibility from the modified object by the global Hilbert transform with a symmetric kernel. b)/c) Regularization of the radiation from a VCSEL/edge emitting laser.

4. Conclusions

We show that the proposed generalized Hilbert transform allows controlling the scattering of light. Following the to design media for the local or global unidirectionality, is a feasible tool for applications. The method allows designing on demand optical responses, in a broad frequency range. We show that the procedure allows engineering frequency
dependent asymmetric light transportation in periodic and non-periodic structures optimized complex permittivity distribution.

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Plasmonics: Fundamentals and Applications
From passive to active manipulation of the polarization states of electromagnetic waves by plasmonic metastructures

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In this talk we focus on both passive and active manipulation of the polarization state of light with 2D/3D plasmonic metastructures. First, we present an efficient approach to tune the phase difference of light in two orthogonal directions by controlling time retardation with a plasmonic metasurface. Second, we demonstrate a general mechanism to construct the dispersion-free metastructure, where the intrinsic dispersion of the metallic structures is perfectly canceled out by the thickness-dependent dispersion of the dielectric spacing layer. By selecting the structural parameters, the polarization state of light can be freely tuned across a broad frequency range, and all of the polarization states on the Poincaré sphere can be realized dispersion free. Third, we demonstrate a freely tunable polarization rotator for broadband terahertz waves using a metastructure and provide an example on dynamically switching the polarization state of light based on the phase transition of vanadium dioxide. Our studies provide some guidelines to control the polarization state of light at the subwavelength scale.

References:
Light Assisted Synthesis of Novel Plasmonic Nanostructures for Single-molecule Surface-enhanced Raman Scattering and Nanofocusing

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Abstract
The introduction of light during the synthesis process brings additional controllable freedom that enables new possibility to tailor the physical parameters of nanomaterials. We have developed a two-step photo-reduction approach to generate highly reproducible single-molecule Surface-enhanced Raman Scattering (SM-SERS) materials. We also shown that photochemical synthesis can create silver nano-needles with high aspect ratio and ultra-smooth surface. These nano-needles are excellent nanofocusing waveguides with divergent effective refractive index for plasmon propagating modes.

1. Introduction
Plasmonic nanostructures have significant potential to be applied on miniaturized optical devices, ultrasensitive sensing and spectro detection [1]. Controlled synthesis for nanostructures is a central task of plasmonics [2]. The introduction of light during the process of nanostructure synthesis brings additional controllable freedom that enables new possibility. Here, we developed two kinds of photochemical methods to obtain novel nanoaggregates and nanowaveguide for single-molecule detection and nanofocusing.

2. Nanoaggregates for SM-SERS microfluidic chips
We have developed a two-step photo-reduction approach and combined with microfluidic chips to generate highly reproducible SM-SERS [3]. In Figure 1, it is shown that the SERS detection limit for various types of molecules can be as low as 10^{-13} M. Standard biamalyte SERS analysis proves that this limit has reached the single-molecule detection level. Furthermore, this approach can be easily combined with microfluidic system to realize on-chip SM-SERS detection with high reproducibility (~50%) and good homogeneity (relative deviation ~30%). Furthermore, we show that the light field distribution can effectively tailor the morphology of chemically synthesized nanostructures.

3. Nanoneedles for nanofocusing waveguides
Plasmonic waveguides have significant potential to be used as a key component in miniaturized optical devices, which are of considerable current interest in nano-photonics. Tapered nanowaveguide is one of the most important waveguide structures because of the ability to channel and focus surface plasmons to the sharp apex to generate enormous near field enhancement, known as nanofocusing. This distinct feature enables light guiding and manipulating at nanoscale confinement, which have been widely applied on high-resolution near-field optical imaging, high-order harmonic generation enhancement and ultrasensitive detection, etc. However, current approaches to realize tapered structures have relied on sophisticated fabrication techniques, such as electron beam lithography and focused ion beam milling. It inevitably introduces inherent surface roughness that substantially degrades the optical performance.

Using focused light, we found an interesting phenomenon that crystallized nano-needles can be synthesized with the diameter and length determined by the Gaussian profile of light spot [4]. As shown in Figure 2, these nano-needles possess well crystallized structures, that is, atomically smooth surface fulfilling the requirement for nanofocusing, which demonstrates promising application on sensitive spectral detection, constructing networks of nanophotonic circuits and novel plasmonic scanning probes.
4. Conclusions

In summary, we developed two kinds of photochemical methods to obtain novel nanoaggregates and nanoneedles for single-molecule detection and nanofocusing. This prototype of single-molecule microfluidic SERS chip can substantially reduce the quantity demands for analytes and improve the detection reliability, which can be used for fast and ultratrace SERS detection and real-time monitoring in analytics and diagnostics. On the other hand, novel nanoneedles can guide plasmons over a considerable distance and adiabatically compress the optical field to the sharp apex with a diameter only several nanometers, and thus can be a good candidate for remote-excitation sources.

References


Plasmonics in near-zero-index media

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Abstract

We investigate surface plasmon polaritons (SPPs) at the interface of a metal and a near-zero index (NZI) medium. Interestingly, these SPPs can be excited directly by free-space radiation as their dispersion lies above the free-space light line, in contrast to the case of conventional metal-dielectric interfaces. We explore unusual phenomena such as impedance matching of a NZI medium with free space and perfect electromagnetic absorption, and present designs for active and passive plasmonic waveguides incorporating NZI media.

1. Introduction

Near-zero index media, such as epsilon near zero (ENZ) and epsilon and mu near zero (EMNZ) media have been extensively investigated for their exotic optical properties. They have been shown to afford greater control over light-matter interactions in applications such as wave front engineering, phase matching for enhanced nonlinear processes, subwavelength wave-guiding and quantum emitter manipulation [1]. Further, phenomena such as waveguide super-coupling, antenna resonance pinning and slow light have been proposed and evidenced using both continuous and engineered (meta-) materials [2]. However, plasmonic phenomena in NZI media have been much less explored, with recent research efforts focused mainly on ENZ modes, realized in sub-wavelength scale systems. Here, we explore SPP excitation and propagation at a metal-NZI interface and discuss some of the unique phenomena related to such SPP modes.

2. Main

The SPP propagation constant at an interface is given by

$$\beta = k_0 \sqrt{\varepsilon_n \varepsilon_d / \varepsilon_n + \varepsilon_d} $$  \hspace{1cm} (1)

where $k_0$ is the free-space wavenumber, and $\varepsilon_n$ and $\varepsilon_d$ denote the relative permittivity of the metal and the dielectric. In the regime $\text{Re}(\varepsilon_m) < -\varepsilon_0$, propagating modes confined to the interface are sustained with their dispersion lying below the light line of the dielectric $\varepsilon_d$. In other words, $\beta > k_0 \sqrt{\varepsilon_d}$, where $n$ denotes refractive index. A necessary condition for SPP excitation is the photon–SPP $k$ vector matching that can be provided by a grating or scatterer, or a coupling medium (prism) such that the light line of the dielectric lies above the light line of the prism (i.e. $n_d < n_p$). This also means that SPPs can be excited by free space radiation if $n_d < 1$. For media with $n_d << 1$, at frequencies away from the immediate vicinity of the metal’s plasma frequency ($\omega_p$), it can be shown that $\beta$ rapidly approaches the light line of the NZI medium (much faster than conventional dielectrics [3]) as shown in Fig 1a. Therefore, the photon–SPP momentum matching condition is satisfied for light incident at the critical angle $\theta_c \approx n_d$, and an above-light-line SPP with a low wavenumber $\approx k_0 n_d << k_0$ is sustained at the metal-NZI interface.

2.1. Proof of principle: A continuous ENZ material on Au

Refractive indices less than unity are found at near-IR wavelengths in ENZ materials such as degenerately doped semiconductors. We choose indium tin oxide (ITO), a transparent conducting oxide with refractive indices less than unity at near-infrared wavelengths. Figure 1b shows the SPP dispersion of the gold-ITO interface along with the light line in ITO ($\text{Re}(\omega) = ck/\text{Re}(n_{ITO})$). Since $n_{ITO} < 1$, its light line crosses from below to above the free-space light line, taking the SPP dispersion that closely follows the dielectric light line, above the free space light line. This enables direct excitation of SPPs by free-space radiation. Figure 1c shows the calculated reflectance of a 400 nm layer of ITO on gold, for p-polarized light incident from air. Absorption under zero transmission, indicated by a reflection minimum agrees well with the SPP dispersion, showing efficient excitation of the above-light-line SPPs at the gold-ITO interface.

2.2. Impedance matching with NZI medium

Achieving impedance matching with NZI media is challenging owing to their extreme optical properties, where the impedance is given by $Z = \sqrt{(\mu_{eff}/\varepsilon_{eff})}$. However, the angle dependent effective impedance of the metal-NZI system can be made to match that of free space [5], enabled by coupling light to the radiative modes excited at the metal-NZI interface. Importantly, impedance matching prevents reflection from the system, resulting in perfect absorption.

2.2.1. Perfect absorption

Complete absorption may be achieved in single channel structures by suppressing the reflection by destructive interference of outward propagating waves. Then, incident
light is perfectly coupled into the radiative modes in the structure by the well-known phenomenon of critical coupling. We show that impedance matching can be achieved even for real materials such as ITO having moderate internal losses, which arises as a natural requirement for critical coupling. The internal damping of the resonator (mode) determines the critical geometric parameters such as NZI thickness and incident angle for perfect absorption.

2.3. A MIM plasmonic waveguide with NZI core

Figure 2: Schematic of the metal – NZI – metal waveguide showing perfect coupling from free space (left), low loss wave guiding in a passive MIM structure (center) and an active wave guide element (right).

2.3.1. Passive wave guide element

Figure 2 shows the schematic of the explored passive and active waveguides for SPPs excited at the metal-NZI interface. The SPPs excited here are leaky modes and radiate into free space, however we show that they can be effectively coupled into a metal–NZI–metal waveguide. The propagation loss of an SPP $\propto n_d^3$ [3] can be dramatically reduced by the low index of the NZI core compared to conventional MIM structures. The efficiency of the free space – waveguide coupling depends on two factors: (i) achieving critical coupling to the metal-NZI SPPs, and (ii) mode matching between these SPPs and MIM waveguide modes, incorporating NZI media. In general, MIM modes have larger $\beta$ than single interface modes. However, as already mentioned, $\beta$ lies close to the light line for an NZI medium ($\beta - k_{\text{NZI}} n_d^3 \propto n_d^3 \rightarrow 0$, as $n_d \rightarrow 0$) and this is also true for a MIM mode with a NZI core. Thus, we can achieve excellent mode matching between the single interface SPPs excited directly from free space and the MIM waveguide.

2.3.2. Active wave guide element

Electrical gating of the MIM structure with a low loss ENZ material core such as doped cadmium oxide allows control over the mode index by driving a thin accumulation layer into ENZ resonance. This causes a large change in the absorption coefficient of the waveguide mode and may be exploited in the design of optical modulators.

3. Conclusions

Surface plasmon modes at a near zero index – metal interface are found to lie above the free space light line, allowing momentum matching and direct coupling with free space radiation. Importantly, this above-light-line SPP is shown to be sustained by a thin ENZ layer of ITO on gold and may be tuned across the communication wavelength (1550 nm). Excitation of this radiative mode demonstrates unique phenomena such as impedance matching and perfect absorption by a NZI medium. Plasmonic waveguides incorporating NZI media can have extremely low loss propagation, achieve highly efficient coupling to free space radiation and form active waveguide elements. The plasmonic MIM waveguide with lossless NZI core is thus a new paradigm in on-chip photonics and light manipulation. Integration of zero index media in plasmonic circuits has the potential to uncover novel phenomena and enable improved control over on-chip manipulation of free space optics.

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References

Colloidal self-assembly route towards efficient designing of nanophotonic architectures

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Abstract:
Current state of the art in the field of plasmonics and nanophotonics often involves strong coupling of different resonant mechanisms that ensures useful applications in enhanced signal processing [1], energy harvesting [2] and fine line shaping with increased sensitivity in opto-plasmonic sensors [3]. In our recent work [3], template-assisted self-assembly (TASA) of metallic nanoparticles (NPs) as 1D plasmonic grating in guided-mode resonant (GMR) photonic structures produced anisotropic coupling between the photonic and plasmonic counterparts. We report gold (Au) NPs self-assembled in a linear template on a titanium dioxide (TiO2) layer to study the dispersion relation with conventional UV-vis-NIR spectroscopic methods. Compared to metallic grids, the experimentally observed (supported by simulation) range of hybridized guided-modes can now be extended to modes along the nanoparticle chain lines. Fabrication of such hybrid-architectures over macroscopic areas through successful confluence of top-down and bottom up approaches like interference lithography and colloidal self-assembly respectively has resulted in polarization-dependent enhancement of plasmonic induced GMR sensitivity. Following the footsteps, we further propose realization of plasmonic metamaterial bases using pre-designed templates fabricated through phase-controlled interference lithography (PCIL) [4, 5]. The driving force behind realization of such organized metamaterial bases using ‘shape-specific’ templates is again the reduction of free energy to reach equilibrium, similar to the cases of simpler 1D grating. Thus PCIL boosts the charisma of ‘self-assembly’ approach in comparison to size-limited, time-limited and cost-intensive electron (ion) beam methods towards realization of programmable, scalable and robust nano-photonic architectures for lighting, photovoltaics, and sensors.

References:
Quantitative characterization of second order nonlinear light conversion from inorganic and organic nano(micro)-structures

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Abstract

Second harmonic generation (SHG) and sum frequency generation (SFG) are the nonlinear optical processes of doubling or summing the frequency of input light by passing it through non-centrosymmetric crystalline materials. Quantitative modelling of their nonlinear processes is of great importance for optimizing nano(micro)crystal based nonlinear photonic devices for applications in frequency conversion, multiplexed signal transmission and noninvasive sensing. Here we demonstrate the quantitative analyses of optical nonlinear conversion in inorganic and organic nano(micro)structures with known and unknown second order susceptibility tensor.

1. Introduction

The optical 2nd order nonlinear conversion process is governed by the materials second order susceptibility tensor. Studying the efficiency of this process can provide data key to the understanding of the materials’ nonlinear optical properties. Here we show systematic methods to do the quantitative characterization of nonlinear conversion by nano(micro)structures in the situation with known and with unknown second order susceptibility tensor.

2. Results and Discussion

2.1. Hybrid plasmonic structures with known 2nd order susceptibility tensor

When the 2nd order susceptibility tensor is known, the conversion efficiency of the SHG and SFG sensitively depends on the ‘mode matching’ conditions at the fundamental and/or SHG wavelengths in the resonant cavity case and on the ‘phase matching’ conditions at the waveguided case. Here we show highly efficient SHG and SFG generation and propagation through hybrid plasmonic structures by exploiting the deep subwavelength scale mode confinement at the fundamental frequencies at the semiconductor-insulator-metal interface [1].

2.2. Identification of the 2nd order susceptibility tensor of organic micro-crystals

Many organic crystals have demonstrated nonlinear properties and possess other useful properties such as high molecular polarizability, relative ease of synthesis and most importantly biocompatibility. Though the identification of 2nd order susceptibility tensor of organic crystals is often hindered by the required crystallographic/geometric corrections [2], here we present a streamlined method for finding the ratio of contribution of each susceptibility tensor element from polarization resolved transmission SHG microscopy using a simple fitting model including geometric corrections via particle swarm optimization. This simple but robust method is applied to different types of amino acid-based microcrystals [3].

Figure 1: (A) Raster scanned optical image of β micro-needle of Glycine in transmission (B) SHG intensity map of same β micro-needle.

3. Conclusions

In summary, we have demonstrated methods to achieve quantitative analyses on SHG and SFG of inorganic and organic nano(micro)structures. This study further widens the applications of nonlinear materials and processes in integrated photonics circuits.
Acknowledgements

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References


Plasmon-Exciton Coupling: Light-forbidden Transitions and Quasichiral Interactions

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Abstract

We present two plasmon-exciton coupling phenomena emerging due to the deeply sub-wavelength nature of surface plasmon (SP) resonances in nanocavities. First, we will investigate the impact that light-forbidden exciton transitions have in the population dynamics and far-field scattering spectrum of hybrid systems comprising nanoparticle-on-a-mirror SPs and three-level quantum emitters (QEs). We will show that the presence of quadrupolar transitions in the QE leads to a strong modification of the usual Purcell enhancement and Rabi splitting phenomenology for dipolar excitons. Second, we will present a combined classical and quantum electrodynamics description of the interactions between two circularly-polarized QEs held above a SP waveguide. We will establish the conditions required to achieve non-reciprocal, chiral, coupling between them. Moreover, by relaxing the stringent requirements for chirality, we will reveal a quasichiral regime, in which the quantum optical properties of the system are governed by its subradiant state, giving rise to extremely sharp spectral features and strong photon correlations.

1. Light-forbidden transitions

First, we explore the impact that light-forbidden exciton transitions have in QE-SP coupling [1]. The emitter is modelled as a V-type three-level system, with dipolar and quadrupolar (dipole-inactive) excited states. The latter are long-lived excitations presenting radiative decay rates typically 5 orders of magnitude lower than dipolar states. They are effectively decoupled from light, but recent theoretical predictions suggest that the large evanescent field gradients associated to SPs may allow Purcell enhancing these transitions up to time scales comparable to light-allowed ones. We investigate this phenomenon beyond the weak-coupling regime and assess its influence in the formation of plasmon-exciton-polaritons at the single emitter level.

We consider an archetypal plasmonic cavity: a nanoparticle-on-a-mirror (NPoM) geometry with a sub-nanometric gap, see Figure 1. Using transformation optics [2], we describe in a fully analytical manner the near- and far-field characteristics of the SP modes supported by this structure.

Figure 1: Left: Sketch of the system under study, A QE (three-level system) is placed at the gap of a metallic NPoM cavity. Right: Far-field scattering spectrum for different values of the quadrupole lifetime. Black dashed lines plot the cross-section for the bare NPoM. Insets: cross section versus laser frequency and $\gamma_Q/\gamma_D$ (arrows indicate the configurations in the main panel). Solid (LPEP), dashed (MPEP1) and connected-dotted (MPEP2) lines render the various PEP dispersion bands, whose Hopfield coefficients are rendered as a function of $\gamma_Q/\gamma_D$ as well.

This provides us with deep physical insights into the population dynamics and the scattering spectrum of the hybrid QE-SP system. We focus our attention on configurations in which light-forbidden transitions yield
strong, but entirely different, modifications of the Purcell enhancement and Rabi splitting phenomenology. This is illustrated in Figure 1. Placing the emitter at the gap center and setting both exciton frequencies at resonance with the lowest SP mode, its lifetime effectively increases and a third peak emerges in the scattering spectrum between the Rabi doublet.

2. Quasichiral interactions

Second, we investigate the interactions between two circularly polarized quantum emitters mediated by surface plasmons polaritons sustained by a flat metal surface [3]. We show that, depending on their position and their natural frequency, the emitter-emitter interactions evolve from being reciprocal to nonreciprocal, which makes the system a highly tunable platform for chiral coupling at the nanoscale. We explore the interplay between QE-QE coherent and dissipative coupling mechanisms [4], revealing a quasichiral regime in which its quantum optical properties are governed by its subradiant state, giving rise to extremely sharp spectral features and strong photon correlations.

Acknowledgements

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References


Figure 2: (a) Effective coupling between two circularly-polarized QEs above a metal surface (left inset) versus their relative position, \(x/\lambda_0\), and for \(z = 5\) nm, \(\omega_0 = 2.35\) eV. Right inset: dissipative coupling versus position. (b) One-photon spectrum (gray line) and its constituents (coloured lines) in the quasi-chiral regime, in which the relative phase between coherent, \(g_{12}\), and dissipative, \(\gamma_{12}\), coupling is fixed to \(5\pi/4\).
Measuring the temperature of plasmonic systems in ultrafast pump-probe experiments

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Abstract

After light-metallic nanoparticles (NPs) interaction, the system subcomponents, such as electron gas, lattice and environment, gradually return to equilibrium by means of complex dynamic relaxation processes. Up to now, the absence of direct experimental method for measuring the dynamic temperature evolution of each system subcomponents was a major hurdle in understanding such processes. In this work, we discuss different methods for directly measuring the ultrafast evolution of the electronic temperature in metallic NPs, impulsively excited by ultrafast radiation pulses.

1. Introduction

Following the interaction of light with NPs, the absorbed energy drives the electron distribution out of thermodynamic equilibrium, generating “hot electrons”; the electron gas then thermalizes due to electron-electron (e-e) interactions over the fs time scale, and cools down by releasing energy to the ion lattice via electron-phonon (e-ph) coupling on the ps time scale\cite{1}. Time-resolved optical and electronic techniques have been extensively used for the study of electron-interaction mechanisms in nanomaterials and to describe the above processes. Nevertheless, especially in the sub-ps regime, existing studies mostly rely on theoretical modeling for the evaluation of the temperature evolution of the NPs after interaction with light\cite{2}.

In this work, we report for the first time two different direct measurements of the ultrafast electron temperature dynamics in gold (Au) NPs. In the first, we compared the ultrafast optical response of Au NPs following pulsed-laser irradiation, by means of pump-probe transient absorbance spectroscopy (TAS) with their static optical response as a function of variable thermodynamic-bath temperature ($T_{\text{bath}}$), in a separate experiment\cite{3, 4}. By this comparison, a dynamic thermometric calibration system was developed which gives us the opportunity to experimentally estimate the delay time for which electron-lattice equilibrium is achieved. In the second method, ultrafast time-resolved-pump-probe Photoemission Spectroscopy (tr-PES) measurements were performed, at the Fermi edge of impulsively excited Au NPs. This way, the temperature evolution as a function of time delay was derived.

These kind of measurements are extremely relevant because they allow a model-independent assessment of the electronic temperature of the Au NPs and since hot electrons generation and relaxation in metallic NPs are indeed of crucial importance for applications such as photodetection and photocatalysis.

2. Discussion

For the first method, the samples consisted of 2D arrays of Au NPs fabricated by solid-state dewetting of ultrathin Au films onto a nanopatterned LiF(110) single crystal. The system exhibits a room-temperature (RT) localized surface plasmon resonance (LSPR) at $\lambda_{\text{LSPR}} \approx 560 \text{ nm}$. The static optical response of the NPs as a function of $T_{\text{bath}}$ was assessed by means of temperature-dependent optical transmittance spectroscopy (400-800 nm range), performed in a home-designed high-vacuum (HV) vessel ($p < 10^{-7}$ mbar). The ultrafast, time-resolved measurements were performed by means of TAS. The laser pulses used for exciting/heating and probing of the 2D arrays were produced by a single femtosecond laser system. The wavelength of the pump pulse was 410 nm while for the probe, white light supercontinuum (SC) pulses (350-800 nm) were generated. In Fig. 1, the electronic temperature evolution of the NPs as a function of time delay is presented as extracted from the analysis of the measurements described above.

By this method the temperature following electron-lattice equilibration is revealed. The results from the comparison of static with dynamic data are in a good agree-
Figure 1: Time dependence of the NP temperature extracted from the comparison between TAS and static measurements.

Figure 2: Electronic temperature evolution of Au NPs as extracted from tr-PES measurements on the Fermi Edge.

...ment with theoretical calculations. This approach can be suitable for e-ph interactions but for short time delays (sub ps-regime) different kind of measurements should be applied.

By performing tr-PES on Au NPs we were able to detect the temperature dynamics and e-gas equilibration due to e-e collisions. This time, Au NPs were deposited onto a thick film (≈ 150 nm) of Al-doped ZnO (AZO). AZO is a transparent conductive oxide and as such, it allowed to perform PE experiments while maintaining a sufficient confinement of electrons within the Au NPs. After AZO deposition, Au NPs growth was performed on top of the oxide surface by solid-state dewetting. The mean size of the NPs is around 20-25 nm and they exhibit a room-temperature LSPR at $\lambda_{LSPR} \approx 600\text{nm}$.

In Fig. 2, we report the electronic temperature of Au NPs as a function of time delay, as extracted from the second spectroscopic method (tr-PES) presented here.

From 0 s (time of the interaction of the ultrafast laser beam with the Au NPs) to 750 fs, a temperature increase is observed related to the energy redistribution among the electrons by e-e scattering (internal thermalization). After 750 fs, the temperature starts to decrease and the system reaches equilibrium after several picoseconds indicating the energy transfer to the lattice by e-ph interaction (external thermalization). Also with this approach our results are in a good agreement with the results expected due to theoretical calculations.

3. Conclusions

We reported two different approaches to extract information on the electronic properties of Au NPs on the ultrafast time scale. The comparison of static with ultrafast optical pump probe measurements generated the development of a calibration system in order to extract the electronic temperature in ps time scale, which corresponds to electron-lattice interactions. Our results are in a good agreement with theoretical calculations. Furthermore, tr-PES revealed the temperature of electrons in the sub-ps regime which corresponds to e-e collisions. The methods reported here are conceptually general, and applicable to all systems.

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References

Multipole Engineering in Silicon Mie Resonator with Cap Layer

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Abstract
We study the mechanism of spectral narrowing of resonant scattering from a silicon Mie resonator by adding a cap layer. Multipole decomposition analysis reveals that lossy materials cause spectral red-shift of electric dipole only and induces the narrowing of Mie resonance.

1. Introduction
Dielectric metasurface attracts much interests in recent years. We studied structural colors based on a silicon (Si) Mie resonator and demonstrated vivid color generation with diffraction-limited resolution of 100,000 dot per inch (dpi) [1]. Such high-resolution color pixel was not achieved by a homogeneous dielectric resonator, but by a dielectric resonator with a cap metallic layer on the top. In order to reveal the mechanism of such effect, we investigate spectral control by adding a thin layer for various metal/dielectric.

In this talk, we report the spectral narrowing and its mechanism of a capped Si Mie resonator. This opens a new pathway to control the scattering of Mie resonator as multipole engineering.

2. Mie resonator with cap layer
Figure 1 shows analyzed meta-atom structures: a cylindrical Si resonator placed on a quartz substrate with and without a cap layer (metal or dielectric). We calculated reflectance spectra for the array of the meta-atom by FDTD simulations. We also calculated electromagnetic filed and scattering cross section (SCS) by Finite Element Method (FEM). Mie coefficients of the meta-atom were obtained by multipole decomposition analysis (MDA) [2]. Here, we are able to analyze each component of multipoles such as electric dipole (ED), magnetic dipole (MD), electric quadrupole (EQ) and magnetic quadrupole (MQ) etc.

3. Results and discussions
Figure 2 shows spectra of reflectance and SCS from the resonator. In the resonator without a cap layer, two main peaks are observed caused by MD and ED as shown in Fig. 2(a) and (c). The additional Cr cap layer modifies reflectance from double peaks to single peak (Fig. 2(b)), resulting in significantly increasing Q-value in Mie resonance. In this case, the MDA calculations suggest that only the peak position of ED is red-shifted and merged to the peak of MD as in Fig. 2 (d), resulting in observing single peak. In addition, we performed calculations for various metals/dielectrics and found that such effects are observed only in lossy materials.

From the above results, we are able to control scattering spectra not only by the shape of a meta-atom, but by an additional cap layer of lossy material placed on it. This opens a new pathway to control the scattering of Mie resonator as multipole engineering.

Figure 1: The schematic view of meta-atoms: (a) Si Mie resonator with height h and diameter d, and (b) with an additional metal/dielectric cap layer with thickness of t and relative permittivity of ε on the resonator.

Figure 2: Reflectance and SCS spectra of the cylindrical Si Mie resonator of h=150nm d=180nm and period P=250nm: (a) (c) w/o Cr cap layer and (b) (d) with lossy metal cap layer (ε=5+20i) of t=30nm. Total SCS and components of MD, ED, MQ, EQ are plotted.
Acknowledgements

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References

The Coulomb Blockade in Plasmonics and How to Optically Lift it.

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Abstract

We propose that a Coulomb blockade can suppress the tunneling current in quantum plasmonics in case of very small nanoparticles. Hence, a redshift is sustained even for sub-nanometer approach. This holds up to moderate fields that do not surpass the Coulomb blockade. Only for stronger optical fields, the Coulomb blockade is lifted and a charge transfer plasmon can be formed.

1. Introduction

It was proposed that quantum tunnelling of electrons prevents the classically predicted divergence of electrical field strength in the hot spot between the nanoparticles [1]. Experimental proof was provided as well [2-3]. However, tunnelling of electrons in quantum plasmonics was so far always considered as a continuous effect where the conductivity between two nanoparticles increases gradually with decreasing distance [4]. Instead of single electrons, electron densities were discussed [5]. In contrast, we recently addressed that the electrical charge and the plasmons are quantized. We propose that the Coulomb blockade of the tunnelling current should prevent the formation of a charge transfer plasmon (CTP) and the system should stay in the classical electromagnetic (CEM) regime until a certain threshold potential is overcome in the gap between two plasmonic nanoparticles [6].

2. Coulomb Blockade

Let us consider a pair of spherical gold nanoparticles, each with radius $R$ and a surface-to-surface distance $d$. If $d \approx R$, then the capacitance can be estimated by $C = 4\pi \epsilon_r \epsilon_0 R$. For example, $R = 2.5 \text{ nm}$ results in $C = 0.278 \text{ aF}$. The potential energy required to transfer a single electron from one to the other nanoparticle by tunneling is then given by the Coulomb blockade energy $U_C = e^2 / (2C)$, where $e$ is the elementary charge. In the specific example, $U_C = 288 \text{ meV}$, which is more than 10 times thermal noise at room temperature and hence should be easily in reach of experimental observation. As a consequence, quantum tunneling should be suppressed and a CTP should not form. Instead, the more intense and redshifted (compared to that of a single nanoparticle) extinction spectrum of the bounding dipolar plasmon (BDP) will be observed.

3. Optical Lifting of Coulomb Blockade

The Coulomb blockade should break down if the potential between the two nanoparticles surpasses $U_C$. At that moment, the spectrum will change from that of a BDP to that of a CTP; this means, it will rapidly blueshift and weaken. In contrast to previous considerations [7-8], we do not assume a potential or charge from outside, but we consider that the optical power provided by an impinging light from outside, driving the BDP, lifts the Coulomb blockade. Hence, the Coulomb blockade is not lifted by a CW field, but by the optical field of approx. 500 THz frequency. The sudden snap from the BDP to a CTP plasmon should resemble a massive nonlinearity at optical frequencies with ample of applications.

4. Discussion

An important obstacle to this concept will be the minimal quantum energy of a single plasmon oscillation on the dimer of gold nanoparticles [6]. If this minimally required energy already causes a potential drop $U_{pl}$ that exceeds $U_C$, the concept will not work out. We will give some examples, where this problem is relevant, and some others where $U_C$ safely exceeds $U_{pl}$. We will further discuss the proposed concept in the light of what is usually termed the “three conditions” of the orthodox theory of Coulomb blockade [9].

References


Plasmonic chirality of one-dimensional nanostructures: the role of lattice resonance

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Abstract

We perform systematic studies of one-dimensional (1D) chains of twisted nanorod dimers, focusing on the collective effect. Our studies reveal that the interplay between local structure/near field interaction and collective effect/far field interaction leads to quite different optical activity than that of the local nanostructures. In particular, it is found that the one-dimensional arrays of achiral objects show chiral responses due to the collective effect. Our studies provide useful guidance for the design of sensors based on optical activity.

1. Introduction

Chirality plays important roles in many fields such as biotechnology and biomedicine. Due to their multifunctionality and tunability, composite nanostructures (with subunits) – “artificial molecules” (with “artificial atoms”), which play the role of basic functional and constitutional unit like molecules in natural material, provide more opportunities for exploring the optical processes, including the chiral optics. The chiral optical response, such as circular dichroism (CD), is due to the combined effects from electric dipole and magnetic dipole moments, which can be modulated by tuning the geometric structure.

We perform systematic studies of one-dimensional (1D) chains of twisted nanorod dimers, paying attention to the collective effect, in particular, the lattice resonance or Wood anomaly. Our studies reveal that the interplay between local structure/near field interaction and collective effect/far field interaction leads to quite different optical activity than that of the local nanostructures. Interestingly, it is found that the one-dimensional arrays of achiral objects show chiral responses due to the collective effect. Moreover, the universal optimal condition for the strongest CD has been found, which is quite different from that of local nanostructures.

2. Theoretical model and approach

Our system is a one-dimensional array of silver nanorod (modelled as ellipsoid) dimers of “fingers crossed ”structure. The plasmonic optical activity of the twisted silver ellipsoid dimers can be modulated by tuning the geometric parameters of the structures. The global geometry is characterized by the lattice constant (LC) d. The correlation between the local structure and the global periodic structure is described by the units’ rotated angle with respect to the x-axis (the chain is along the y-axis). In this paper, we focus on collective chirality due to the interplay between the local intra-dimer interaction within the unit and the inter-dimer interaction among the units. We have performed systematic studies by using coupled dipole model (CDM) and finite-differential time-dominant (FDTD) simulation.

3. Results and Discussion

Figure 1 shows the circular dichroism (CD) of 1D chain of silver nanorod versus the local twist angle, which clearly shows different features than that of a single dimer unit.

![Figure 1: Circular dichroism of 1D chain versus twist angle.](image)
Figure 2 shows $\Delta CD = CD(\text{max}) - CD(\text{min})$ versus wavelength for each frequency in systems with different lattice constants. We’ve seen sharp peaks appearing at the wavelength near the lattice constant due to lattice resonance, which may have applications in sensing based on chiral optics.

![Graph showing ΔCD versus wavelength for 1D twisted dimer chain with different lattice constants 522nm, 530nm and 540nm.](image)

**Figure 2:** ΔCD versus wavelength for 1D twisted dimer chain with different lattice constants 522nm, 530nm and 540nm.

### 4. Conclusions

Based on FDTD simulation and CDM, we have studied the optical properties of 1D chains of twisted Ag nanorod dimers systematically. It is found that the combination of the local geometric configuration and the collective effect leads to novel chiral optical properties. Interestingly, the 1D chain made of achiral unit may lead to a significant chiral signature. The lattice resonance results in a sharp chiral CD peak. Moreover, the universal optimal configurations of the strongest CD have been found. Our results not only deepen our understanding of the optical chirality at the nanometer scale, but also provide useful guidance for the design of nano-sensors with high sensitivity.

### Acknowledgements

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Observing strong coupling in individual plasmonic cavities

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Abstract

We utilize individual plasmonic bowties as cavities to couple to a small number of quantum emitters. Devices with one to several semiconductor quantum dots demonstrate vacuum Rabi splitting in light scattering spectra and in electron energy loss spectra. Data analysis shows that our systems are within or at the onset of the strong coupling regime. Photoluminescence studies demonstrate antibunching from single quantum dots within plasmonic cavities, paving the way to cavity QED studies at room temperature.

1. Introduction

Plasmonic cavities (PCs) are nanometric structures that focus electromagnetic (EM) fields to sub-diffraction volumes through the effect of surface plasmon excitations. The deep sub-diffraction volumes of the EM modes of PCs make them attractive for quantum optical applications. PCs are often made of metallic nanostructures, and rely on the concentration of the EM energy in gaps between particles or at sharp tips or corners. We have recently demonstrated that such nanofocusing can strongly couple single plasmonic cavities and quantum emitters, based on a series of spectroscopic techniques. We introduce below our results, both published [1-3] and unpublished [4].

2. Strong coupling with quantum dots

We inserted colloidal quantum dots (QDs) into silver bowtie structures and studied their spectroscopy [1]. Light scattering spectra of individual devices clearly showed a dip indicative of vacuum Rabi splitting, the hallmark of strong coupling, in the presence of one, two or three QDs in the PC gaps (Figure 1). Analysis of the spectra using a coupled-oscillator model showed that the coupling of individual QDs could be as high as 120 meV. More recently, we also found that fast electrons within the electron microscope can probe this coupling, based on electron energy-loss spectroscopy (EELS), but now with nanometric spatial resolution [5]. Interestingly, EELS experiments allowed us to observe coupling of QDs to a dark, subradiant mode of the plasmonic bowtie (Figure 2). Calculations showed that the dark mode is strongest at the periphery of the PC gap, which is where QDs should be placed for efficient coupling.

We also studied photoluminescence (PL) from QDs coupled to PCs [4]. Hanbury Brown and Twiss experiments demonstrated strong antibunching, with a signal at time zero indicative of an individual QD within the PC. Surprisingly, PL spectra could not be understood as simply arising from the two polaritonic levels formed by coupling of the QD’s bright exciton to the plasmon. Quantum mechanical calculations demonstrated that a dark exciton of the QDs becomes bright enough to appear in the spectra. The intensity of the PL emitted by this dark exciton is affected in a non-trivial manner by the bright state’s polaritonic levels [4]. The coupling of the QDs to plasmons thus emerges as a way to manipulate excited-state dynamics and observe novel relaxation pathways.

3. Conclusions

Plasmonic strong coupling holds the potential to serve as a new testbed for quantum optics and chemical dynamics under ambient conditions. Our studies and others’ have made the first steps in this direction. Much research remains to be
performed in order to outline the unique features of plasmonic strong coupling and utilize them for novel applications.

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References


Tunable Optical Response of Plasmonic Au Nanoparticles Embedded in Ta-doped TiO₂ Transparent Conductive Films

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Abstract

Localized Surface Plasmon Resonances (LSPR) of Au nanoparticles can be tailored in the visible range through nanoparticle geometry. However modulation is limited by the fixed carrier density of metals. Embedding Au nanoparticles in Transparent Conductive Oxides (TCOs) is an original approach to widen LSPR tunability by acting directly on the surrounding host. In this contribution we show that the easily modifiable permittivity of the TCO matrix succeeds as an additional degree of freedom in tuning properties.

1. Introduction

The field of plasmonics for light manipulation at the nanoscale has been dominated by nanostructured noble metals, e.g. Au nanoparticles (Au NPs), due to the possibility to control the LSPR in the visible with size and shape, as well as NP surrounding [1]. However, tunability through geometry is constrained by the non-modifiable charge carrier density [2]. Hence alternative approaches become essential in order to activate and widen novel plasmonic functionalities outside the visible spectrum. Recently, attention has been directed towards metal-semiconductor nanocomposites [3]. These architectures possess an inherent multifunctional nature, enabling unique properties to be reached resulting from the combination of different physics owned by the metal-host couple [4]. Besides, by exploiting the dependence of LSPR from material surrounding [1], larger tunability of the conventional plasmonic response of Au NPs can be achieved in an indirect way. In this framework, Transparent Conducting doped Oxides (TCOs) have emerged as very advantageous choices for matrices in nanocomposites. Apart from their optimal characteristics for optoelectronics (e.g. transparency and metal-like conductivity [5]), morphology and stoichiometry control at synthesis provide exceptional carrier concentration modulation [6]. This is a fundamental aspect in nanocomposite design, that can be exploited as a powerful tool to engineer the dielectric function without changing the material.

In this work, a metal-TCO nanocomposite has been fabricated by embedding Au NPs in the less-explored Tantalum-doped TiO₂ (Ta:TiO₂) TCO films, obtained through thermal evaporation of Au, Pulsed Laser Deposition (PLD) of Ta:TiO₂ and multiple ad-hoc thermal treatments. Thermal de-wetting from Au layer is exploited to create NPs. PLD was selected for the well-known capability to master the TCO morphology and composition by operating directly on synthesis parameters [6]. This study aims at tailoring experimentally the Au LSPR by manipulating the surrounding matrix using two approaches. First, the role of the configuration has been analysed by incorporating Au NPs, with fixed diameter of 25 nm, in different positions in the films where they should experience different electrical permittivity [3]. Ta:TiO₂ and Au NPs have been combined in a “bottom” configuration (Fig. 1a), where NPs are positioned between the substrate and the TCO, and in a fully embedded “sandwich-like” set-up (Fig. 1b). The second method consists in varying the Ta doping level in the TCO (5-10% at. and bare TiO₂) to exploit a permittivity change of the matrix. Extensive optical analyses have been performed (UV-VIS-NIR spectroscopy and Spectroscopic Ellipsometry) although attention is also given to the effect of Au inclusion on morphology, crystalline structure and electrical properties by means of Raman spectroscopy and

![Figure 1: SEM cross-sections and associated sketches of Au bottom (a) and Au sandwich (b) configurations.](image-url)
Hall effects measurements, aimed at totally understanding the optical response of the nano-systems.

2. Results and discussion

Au NPs act as nucleation centres for subsequent TCO deposition (Fig. 1a,b) which partially degrade structural and electrical properties, both for bottom and sandwich composites. Nevertheless, these composite systems combine at once good conductive and plasmonic characters, hence are potentially attractive as novel optoelectronic metamaterials. Here, we focus on the optical response of Au sandwich configuration, demonstrated as the most effective in shifting the plasmon resonance. A stronger effect of the dielectric permittivity is expected for Au sandwich because Au NPs are completely immersed in the TCO and feel the largest variation in surrounding, with no influence from the substrate. Indeed, fully-embedded AuNPs experience the largest plasmonic modulation, with a considerable red shift (550-800 nm) and broadening of the transmittance minimum associated to Au LSPR (Fig. 2a) compared to air-exposed substrate-supported nanoparticles. This behavior is attributed mainly to the sensitivity of the plasmon peak to the dielectric function of the surrounding. Notably, when changing the doping degree in TiO$_2$-based hosts (0%, 5%, 10% Ta), i.e. by decreasing the real dielectric permittivity $\varepsilon_1$ (Fig. 2b), the plasmon position is efficiently blue-shifted gradually from 780 nm in TiO$_2$ to 670 nm in Ta(10%):TiO$_2$. This behaviour agrees with the trend of the peak in the imaginary permittivity $\varepsilon_2$, connected to plasmon absorption. When comparing LSPR responses of Au bottom and Au sandwich films as a function of $\varepsilon_1$ of the embedding host (Fig. 3), the sandwich is established as the configuration which mostly tune the Au resonance. In fact, in both systems embedded Au NPs are subjected to a strong red-shift compared to air/glass exposure, but in Au bottom no significant trend as a function of TCO doping is observed. In addition, the connection between LSPR and $\varepsilon_1$ can be clearly identified. LSPR shift between 5% and 10% Ta TCOs is scarce compared to TiO$_2$ media, reflecting the appreciable difference in permittivity between bare TiO$_2$ ($\varepsilon_1$=6.2) and Ta$_2$TiO$_5$, which instead experiences limited variation between Ta 5% ($\varepsilon_1$=5.6) and Ta 10% ($\varepsilon_1$=5.4) doping. However further investigation is required to identify the contribution of size/shape of NPs, or charge transfer mechanisms on the LSPR shift.

Figure 2: (a) Transmittance spectra and imaginary permittivity $\varepsilon_2$ (b) of Au sandwich films with different Ta doping of the matrix (5, 10% at. TCOs and bare TiO$_2$). Au NPs (black) on glass substrates are shown for reference.

Figure 3: Plasmon resonance of Au NPs ($\lambda_{LSPR}$) as a function of surrounding hosts (Au bottom and Au sandwich). Values of real permittivity $\varepsilon_1$ of the corresponding matrices are shown for reference.

3. Conclusions

Nanocomposites made of Au NPs and Ta:TiO$_2$ TCO films have been synthesized through a “multistep” approach. The lowest resistivity reaches 1.5x10$^{-1}$Ωcm in Au-Ta(10%):TiO$_2$ architectures. Au LSPR is successfully controlled by operating directly on the dielectric properties of the surrounding through the configuration of NP integration (bottom and sandwich) and the Ta level in the TCO. For sandwiches, the LSPR is efficiently blue-shifted by increasing the Ta doping content. Au-added Ta:TiO$_2$ nanocomposites films are promising as highly tunable plasmonic conductors for potential integration in complex metamaterials and optoelectronic devices for enhanced light management (e.g multifunctional transparent electrodes).

References

Electron Dynamics in Plasmons

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Abstract

We show that the Particle-in-Cell (PIC) simulation method can be used to robustly describe plasmon resonances, with a unique emphasis on the motion of the electrons in the time domain. Laser-excited and electron-beam-excited plasmons are studied to obtain the femtosecond time-scale dynamics of electrons in plasmons, including the plasmon dephasing, the electron kinetics during damping and the evolution of plasmons and electrons during interaction with an electron beam.

1. Introduction

Plasmons are the collective oscillations of conduction electrons in metals. Theoretically, plasmon resonances are usually investigated by solving the Maxwell equations with a fixed dielectric function inside each material boundary, for example with FDTD in the time domain and BEM in the frequency domain. Such an approach overlooks the motions of electrons, especially at the material boundaries. To fill this lacuna, we attempt to use Particle-in-cell (PIC) simulations, a method widely used to study plasmas, and apply it to simulate plasmon resonances [1]. In PIC, materials are represented by their free conduction electrons. Maxwell’s equations and equations of motion of these electrons are solved iteratively for each of the conduction electrons, to obtain the time-evolution of the electromagnetic fields and electron trajectories. This method will be used to study electron dynamics in laser-excited and electron-beam-excited plasmons.

2. Plasmons excited by laser

We simulate a gold nanorod excited by a 10 fs laser pulse near the resonance frequency. The energy picture of the plasmon excitation and damping is calculated and shown in Figure 1(c), showing the contribution of each energy component and how they evolve dynamically in time. Kinetic induction is visualized through the velocity distribution of the electrons along the oscillation direction (y-direction) in Figure 1(b). The shape of the distribution maintains throughout a plasmon cycle and only shifts along the velocity axis. Therefore, this shows that almost half of all electrons move in the opposite direction of the plasmons, and only a small offset near Fermi velocity constitutes the plasmon oscillation. This is the first important and rather unexpected result from our simulations.

![Figure 1](image-url)

Figure 1: (a) Electric field lines of a 100 nm long and 20 nm wide gold nanorod excited with a laser at 729 nm. (b) top – velocity distribution of all the conduction electrons in the y-direction in time; bottom – energy oscillation in a plasmon cycle (c) Calculated plasmon energy oscillation throughout the simulation time period. [2]

3. Plasmons excited by an electron beam

Particle-in-cell simulation also allows robust simulations of near-relativistic electrons inside the electron microscope. For example, we simulate a gold dimer that is locally excited by an 80 keV focused electron beam at the tip of the gold
rod. Coupling between two rods can also be simulated as presented in Figure 2(b). Furthermore, we study how plasmons form and evolve during the interaction between the metallic nanostructure and the electron beam, and are able to track the motions of electrons while they participate in various plasmon modes. The dynamics of the incoming fast electron can also be obtained, such as its deflection angle and velocity reduction due to the interaction with the lateral plasmon field. This simulation framework can therefore be combined with experimental electron energy-loss spectroscopy (EELS) in the electron microscope to gain new, nanometer-scale insight into the dynamics of electron-plasmon interaction.

Figure 2: (a) Time evolution of the interaction between a fast electron beam and a gold nanorod, using a colormap of the electric field along y-direction. (b) Coupling of a nanorod dimer with a gap size of 10 nm.

4. Conclusions

The Particle-in-Cell (PIC) simulation method is used to investigate the motions of electrons during plasmon oscillations. First, we study laser-excited plasmons to obtain insights into the femtosecond time-scale dynamics of electrons in plasmons, including the plasmon dephasing and the electron kinetics during damping. Secondly, we simulate in the time-domain the local excitation of plasmons by a fast-moving electron for combining with experimental electron energy loss spectroscopy (EELS). We study how plasmons form and evolve during the interaction, and track the motions of electrons while they participate in various plasmon modes.

Acknowledgements

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References

Deciphering Mode-Coupling Mechanism in Extraordinary Optical Transmission via Signature Fano Resonance for Active Tuning

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Abstract

We report on an investigation that aims at deciphering the mode-coupling mechanisms in extraordinary optical transmission (EOT). The EOT phenomenon, being extraordinary, is also intriguing in the interplays between its modes or mode-couplings. Understanding the coupling mechanism would pave the way to the next advances such as active- or on-command tunable EOT. A seemingly simple EOT structure is actually a complex set of cross-coupled oscillators. We conduct computational experiments to decipher the coupling mechanism through the Fano resonance signature. The results provide insights and guidance to structural designs for tunable EOT.

1. Introduction

Extraordinary optical transmission (EOT) phenomena have been observed, first by Ebbesen et. al. in the 90’s [1] followed by many others [2,3]. Being extraordinary, it naturally resulted in numerous researches and practical applications, including ultrasensitive sensing, color filtering, optical focusing, etc. However, underlying EOT is a complex system of cross-couplings of modes (or oscillators) that makes its understanding necessary before innovative extensions, for example, into the future directions of active-EOT or on-command tuning of EOT, or nonlinear optical up- or down-conversions (classical or quantum mechanical).

There can be a number of modes in the play, e.g. the localized ones at the entrance and the exit of the subwavelength aperture and the delocalized surface modes, on both sides, that are ‘brighter’ or better coupled to the far-field electromagnetic radiations via the ‘2D-grating’. In fact, the 2D-grating not only serves as a coupler to the surface plasmon polariton (SPP) mode but could also modulate its dispersion or changes the optical density of states. The latter could in turn affect the light-matter interactions to our benefits (e.g. tuning), or to our detriments, if not understood.

A close look at a typical EOT spectrum, figure 1(a), would reveal a spectral feature that is signature of the Fano resonance between two coupled-oscillators (modes). Fano explained similar absorption spectra in light-atom interactions with coupled-oscillators, and showed that under certain conditions, one of the oscillators could transfer (couple) all its energy to the other [4] and giving rise to an asymmetric spectral profile like the one seen in EOT, fig.1(a). This provides a good access to the underlying mechanism by probing the possible couplings via computational experiments.

2. Decipher coupling-mechanism via Fano resonance signature and computer experiments

We consider a silver layer of finite thickness on a dielectric silicon oxide (SiO\textsubscript{2}) subrate that is perforated with a triangular lattice of holes, as shown in the FIG.2 (a). A far-field broadband plane-wave impinges the top surface at normal incidence. The periodicity (P=560 nm) will serve as a dimensional unit, in the computer experiments.

![Fano spectral signature in the red ellipse computed for the EOT structure in the FIG. 2(a). D is the diameter of each hole, while H is the thickness of the silver layer. (b) Varying thickness H, i.e. coupling between the top surface SPP-grating mode to the bottom dipole radiation mode, the asymmetric Fano profiles become symmetric and transmission decreases.](image)
In this set of experiments, the Fano signature spectral feature in FIG. 1(a) and the EOT peak value are seen to effectively controllable through varying the coupling strength between the SPP-grating mode on the top surface and the Rayleigh dipolar radiation mode of the bottom subwavelength aperture. The asymmetric Fano spectral feature becomes symmetric while the transmission peak decreases as the coupling weakens. The absolute magnitude of the z-axis electrical field (E_z) distribution over the fig. 1(a) sample at \( \lambda = P \) is displayed in the FIG. 2(b). The strong field confined at the rim of the aperture on the top surface implies the surface plasmonic resonance.

FIG. 2 (a) The EOT structure modeled in this study. P is the periodicity of triangular hole arrays, D is the diameter of holes, and H is the thickness of the silver layer. D=0.5P, H=0.14P. (b) The z-axis electrical field (E_z) distribution at \( \lambda = P \). The strong intensity at the rim implies surface plasmon resonant excitation on the top interface.

FIG. 3 (a)(c) The real part and imaginary part of E_z at \( \lambda = 1P \). (b)(d) The real part and imaginary part of E_z at \( \lambda = 1.2P \). Note that \( \text{Re}[E_z] + \text{Im}[E_z] = |E_z| \text{ e}^{\phi} \). The extracted values: \( \text{Re}[E_z] = -1.58, \text{Im}[E_z] = i3.97 \) at \( \lambda = 1P \), and \( \text{Re}[E_z] = 1.75, \text{Im}[E_z] = 11.19 \) at \( \lambda = 1.2P \).

The FIG. 3 (a) and (b) are the real part of E_z at \( \lambda = P \) and \( \lambda = 1.2P \), while (c) and (d) are the imaginary part of E_z at \( \lambda = 1P \) and \( \lambda = 1.2P \), respectively. Here in addition to E_0 on the top surface of the Ag layer, where surface plasmon resonance occurs, we can see the difference in phase (\( \phi \)) which can be obtained from \( E_z = |E_z| \text{ e}^{\phi} \). The phase of E_z at \( \lambda = 1P \) is 111°, while the phase at \( \lambda = 1.2P \) is 34°. The phase difference between these two wavelengths is 77°. This is another less apparent feature that is consistent to what is expected in Fano resonances: a drastical change in phase around the resonant frequency. The incident plane wave are coupled via the grating effectively into surface plasmons on the top surface, which are longitude wave.

Up to this point, the spectral minim (zero) at \( \lambda = 1-1.3P \) is simply assigned to the mode localized to the aperture at the bottom interface as the Rayleigh radiating dipole mode. That would have been more of a wishful assertion or hypothesis of ours than a fact. Another set of computational experiments was therefore conducted to validate the hypothesis. Results, shown in figure, clearly demonstrate that by tuning the substrate (or over-layer), the Fano signature minim and peak would change accordingly.

Fig. 4 (a) The EOT spectrum changes with the substrate's refractive index. (b) The corresponding change with the refractive index of the over-layer.

As for the second spectral peak in the FIG.1 (a), using the same analysis, one can show that it too is attributable to the subwavelength aperture coupling to SPP induced at the bottom interface between silver and SiO_2.

In sum, this work probed the mode-coupling mechanism in EOT in a set of computational experiments. The findings offer not only insight into the operational mechanism but also guidance for future innovations and advances, such as active-EOT via effective coupling to a tunable medium.

3. References


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THz plasmons in AlGaN/GaN grating gate structures at 4K and 300K

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Abstract

Terahertz plasmon resonances were studied at 4.2K and 300K in GaN-based grating gate structures using two THz spectroscopy techniques: Fourier-Transform Infrared Spectroscopy and Time Domain Spectroscopy. Gratings of different periods were coupled to the two-dimensional electron gas in AlGaN/GaN in order to investigate the dispersion law of 2D-plasmons. The plasmon frequency was tuned by the gate voltage both, at 4.2K and 300K. Observation of the tunable plasmons at room temperatures opens the way for high temperature THz plasmonic devices.

1. Introduction

Plasmonic devices arouse great interest for terahertz (THz) frequency range detectors and emitters. Simple example of a plasmonic device is Field Effect Transistor (FET) with high mobility 2D electron gas (2DEG) channel. Estimates for the real parameters of FET show that the frequencies of plasma excitations of charge carriers (plasmons) in the transistor channel lie in the THz frequency range and can be tuned by gate bias and drain current [1]. However, there is an important issue of effective coupling between long-wavelength THz radiation and short-wavelength gated plasmons. One of the possible solutions is the integration of the 2DEG with a metallic grating coupler. This approach was proved already for GaN-based plasmonic grating gate structures [2-4]. However, a room temperature operation and plasma frequency tunability of plasmonic devices still remains puzzling, in particular, when non-laboratory demonstration of FET based devices is considered.

2. Investigated grating gate plasmonic structures

For our investigation, AlGaN/GaN heterostructures were grown by Metal Organic Chemical Vapor Deposition (MOCVD). The epilayers consisted of 2 nm GaN-cap, 25 nm Al0.25Ga0.75N barrier layer, 0.7 - 0.9 μm intentionally undoped GaN layers, and 1 - 2 μm high resistive GaN:C buffer. All epilayers were grown on semi-insulating 6H-SiC substrates. The ohmic source and drain contacts were formed by thermal evaporation of Ti/Al/Ni/Au (150/1000/400/500Å) metal stack and following rapid thermal annealing at 800 °C in nitrogen atmosphere for 60 s. Ni/Au grating gate couplers were patterned by electron beam lithography on a large area (up to 2x2 mm²). Schematic cross section of investigated plasmonic structures is shown in Fig. 1a. Optical microscope and SEM images of one of the studied devices are shown in Fig. 1b and Fig. 1c, respectively. Parameters of all investigated structures can be found in Tab. 1, where 2DEG density and electron mobility are given for the temperature of 4.2 K.

Figure 1: Cross section of investigated plasmonic structures (a); Optical microscope photo of the grating gate with 2x2 mm² active region (b); SEM image of a grating segment (c).

<table>
<thead>
<tr>
<th>Structure ID</th>
<th>Grating period (P) [μm]</th>
<th>Metal length (L) [μm]</th>
<th>2DEG density x10¹⁵ [cm⁻²]</th>
<th>Electron mobility [cm²/Vs]</th>
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</thead>
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<tr>
<td>T1</td>
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<td>3.15</td>
<td>0.97</td>
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<td>1.10</td>
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<tr>
<td>B2</td>
<td>1.5</td>
<td>1.15</td>
<td>0.90</td>
<td>9 140</td>
</tr>
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</table>
3. Results and Discussion

Fourier-Transform Infrared (FTIR) transmission spectra of all investigated plasmonic grating gate structures exhibit plasmon resonance at the frequency defined as \( f_p = s/k/2\pi \), where \( s \) is the plasma velocity, and \( k \) is a plasma wave vector defined by a reciprocal lattice vector of the metal grating as \( k = 2\pi n/P \), where \( P \) is a grating period, and \( n \) is an integer number. Transmission spectra of B2 structure are shown in Fig. 1 as an example. Linear dispersion relations were confirmed for all plasmonic devices (see inset of Fig. 1), which is a typical characteristic of gated 2D-plasmons. The extracted values of plasma velocity were comparable for all the structures at the gate voltage \( V_g = 0 \) V and had the mean value of \( 1.82 \times 10^5 \) cm/s.

At room temperature, we investigated 2D plasma frequency tunability by Time Domain Spectroscopy (TDS) technique (Fig. 3). Due to high signal to noise ratio ~100 dB at 1 THz and a linear polarization of the THz radiation which was matched to the direction of gated plasmonic oscillations a tunability of 2D-plasmon resonances was observed in a wide range of gate voltages (see the inset of the Fig. 3). Gated plasmon frequency as a function of gate voltage can be written as:

\[
f_p = \frac{1}{2\pi} \sqrt{\frac{eV_\phi}{m^*}} \frac{2\pi n}{P},
\]

where \( V_\phi = V_g - V_{th} \) is the gate voltage swing, \( V_{th} \) is the threshold voltage, and \( m^* \) is the effective electron mass. It should be noted that with an increase of a temperature to 300 K, the resonant frequency of 2D plasmons experiences the red-shift (lowering of the frequency) (compare black and magenta experimental data points shown in the insert of the Fig. 3). Although a straightforward explanation of this observable can be given by the effect of temperature dependence of the electron effective mass [4], we admit that at this point such interpretation is only tentative and requires further experimental as well as theoretical confirmation.

4. Conclusions

Plasmon resonances have been studied in grating gate AlGaN/GaN plasmonic devices using THz FTIR and TDS spectroscopies. The resonant frequencies observed in the measured transmission spectra correspond to the gated 2D-plasmons with wave vectors defined by the reciprocal lattice vectors of the metal grating coupler. The investigation of plasmonic structures with different grating periods confirms the linear dispersion relation of gated plasmons. Additionally, a tunability of the plasmon frequency by applying the gate voltage was demonstrated at both, 4.2 K and 300 K. Alone this result is very promising for developing plasmonic THz devices operating in a wide range of temperatures, in particular, the non-cryogenic ones.

Acknowledgement

Financial support of the IRAP Programme of the Foundation for Polish Science (grant MAB/2018/9, project CENTERA) is gratefully acknowledged. The partial support by the National Science Centre, Poland allocated on the basis of Grant Nos. 2016/22/E/ST7/00203, 2017/27/L/ST7/03283, and 2019/35/N/ST7/00203.

References

CQED in hybrid nanophotonic structures

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Abstract
We first propose an approach that combines a photonic crystal and metallic nanoparticle structure to create nanocavities with both strong local-field intensity and high helicity, where both strong and weak couplings with unidirectional propagation are obtained. Then, we propose the mechanism of edge state-led mode coupling under topological protection. Based on this mechanism, in topological photonic structure containing a resonant plasmon nanoantenna, an obvious absorption reduction in the spontaneous emission spectra appears.

1. Chiral cavity quantum electrodynamics (CQED) with coupled nanophotonic structures
As we have known, it remains challenging to couple photons into a photonic structure to simultaneously realize strong photon-emitter interaction and unidirectional propagation. Here, by combining a photonic crystal and metallic nanoparticle structure to create nanocavities with both strong local-field intensity and high helicity, we obtained that the rate of circularly polarized photons emitting into the photonic crystal waveguide reaches 148γ0, as shown in Fig. 1 [1]. In the ultranarrow band-edge mode, the linewidth of Rabi splitting spectra is about one-tenth of that with the nanoparticle only. For both cases ≈95% of photons propagate unidirectionally along the nanoscale waveguide. It suggests that this work establishes a nanophotonic interface of chiral quantum electrodynamics for on-chip nonreciprocal quantum light sources, quantum circuits, and scalable quantum networks.

2. Absorption Reduction of Large Purcell Enhancement Under Topological Protection
We first propose the mechanism of edge state-dominated mode coupling under topological protection. As shown in Fig. 2, based on this mechanism, in the topological photonic structure containing a resonant plasmon nanoantenna, an obvious absorption reduction in the spontaneous emission spectra appears due to the near-field deformation around the antenna induced by the edge state. This topological state-led mode coupling mechanism and induced absorption reduction, will have a profound effect on the study of composite topological photonic structures and related micro- and nanoscale CQED. Also, nonscattering large Purcell enhancement will provide practical use for on-chip quantum light sources, such as single-photon sources and nanolasers.
Figure 2: Schematic diagram of topological state-led mode coupling mechanism and Absorption reduction under topological protection.

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Exotic Meta-media - Time-dependent, Nonlocal and Other Novel Responses
Nonlocal and Soft Plasmonics in Ion Particle Chains

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Abstract

Plasmonic properties of charged fluids are discussed via a two-fluid model. Additional degrees of freedom (ion mass, ion charge, concentration) allow a wide range of bulk resonance frequencies. In analogy to metal nanoparticles, I include commonly neglected charge interactions thus deriving analytic expressions for nonlocal Mie coefficients for coupled charge carriers. Plasmonic ionic response is studied in microspheres and chains and compared to metal systems.

1. Soft Plasmonics

Plasmonics is often understood as a phenomenon in metals, where the free conduction band electrons are oscillating collectively in response to an external electromagnetic field [1]. However, any type of charge carriers can be excited by electromagnetic waves, including coupled charge carriers such as electron-hole pairs in semiconductors [2, 3] and in fluidic ionic systems, e.g. electrolytes [4, 5, 6]. In addition to the presence of ionic plasmons, classical electrodynamics typically neglects interaction between strongly confined charges. This spatial dispersion or nonlocality becomes prominent in metal nanoparticles [7, 8, 9, 10] and its influence on coupled charge carrier systems is explored in more detail in this work and compared to the effects observed in metal nanoparticles.

I investigate ionic plasmonic response in analogy to metal nanostructures with the aim to find a novel perspective on phenomena in biological systems, e.g. nerve cell communication, and chemical processes, e.g. in electrolytes and photocatalysis. In contrast to plasmons in solid nanoparticles, additional degrees of freedom are available. The ion mass $m_\pm$, and charge $Q_\pm$ can be chosen with the material, and the overall concentration $n_\pm$ of ions can be altered. Previously, spherical ions were studied with Random Phase Approximation (RPA) [4, 5], where a fictitious jellium is needed.

2. Two-fluid model

I have shown recently [6], that similar to metals, ionic plasmons can be derived within classical electrodynamics, introducing a two-fluid model for positive and negative ionic charges, without the need for an additional jellium. In contrast to metals, where the mass equals the electron mass $m = m_e$ and the charge is the elementary charge $Q = e$, such ion systems become highly tunable through the choice of materials (if possible) and their concentration $n_\pm$. Due to their high mass, the ionic bulk plasmon frequency of ions lies in the far infrared (> 3μm, GHz-regime)

$$\omega_{p\pm}^2 = 4\pi Q_\pm^2 n_\pm/m_\pm.$$  (1)

To achieve such geometries experimentally, lipid membranes filled with a cytoplasm can be used to confine charge carriers. The coupled system yields an effective localized surface plasmon resonance (LSPR) for spherical geometries at

$$\omega_{\text{LSPR}} = \sqrt{(\omega_{p+}^2 + \omega_{p-}^2)/3\kappa}.$$  (2)

Using multiple scattering techniques [11, 12], I study the plasmonic properties of both single ionic spheres and more complex structures, such as chains of ions in comparison to solid metal nanoparticles. My approach to the optical response of an ionic system with free negative and positive charges in an else neutral fluid is based on the hydrodynamic model [6].

Separating the dynamics of both types of ions from the polarization of the background $\epsilon_0$, I assume $\nabla \vec{D} = \nabla \epsilon_0 \vec{E} = 4\pi(\rho_+ - \rho_-)$ where $\rho_\pm$ are the (external) charge densities. The total charge is balanced, i. e. the charges are mutually compensated by setting $[n_+ Q_+ \equiv n_- Q_-]. This yields an equal density $n = n_+ = n_-$ of charges in cases like hydronium and hydroxide (splitted water molecules) and sodium chloride with equal, but opposite charges.

The electromagnetic wave equation then reads

$$\nabla \times \nabla \times \vec{E} - k^2 \epsilon_0 \vec{E} = \frac{4\pi ik^2}{\omega} \left( \vec{j}_- + \vec{j}_+ \right).$$  (3)

Hereby, $\vec{j}_\pm$ are the charge current densities of the ions in the electrolyte.

3. Coupled nonlocal wave equations

In the hydrodynamic model, the induced current density $\vec{j}_\pm$ is determined with the linearized Navier-Stokes equation for a charged plasma

$$\vec{j}_\pm = \frac{i}{\omega + i\gamma_\pm} \left( \frac{Q_\pm^2 n_\pm}{m_\pm} \vec{E} - \nabla \rho_{\text{GNOR}\pm} \rho_\pm \right).$$  (4)

The pressure term can be derived from classical gas theory and including further quantum mechanical effects, in
particular Coulomb interaction, it was shown that the nonlocal interaction strength [1] yields $\beta^2 \equiv \frac{1}{2} v_F^2$, for metals, where $v_F$ is the Fermi velocity of the material defined as $h k_F = \vec{p} = \vec{v}_F m_e$. In case of heavy ions, I rely on the thermal velocity of the ions $v_{th} = \sqrt[3]{3 k_B T/m}$, which is much smaller than the velocities defined for free charges in solid materials ($v_F = 1.4 \times 10^5$ m/s for Au and Ag) due to the large masses involved ($v_{th} \sim 10^3$ m/s for hydroxide and hydronium, sodium and potassium chloride).

From the continuity equation $i \omega \rho = \nabla \phi$, I find for each type of charge a wave equation coupled to each other

$$\rho_\pm = \frac{\epsilon_b}{\omega^2 \epsilon_{GNOR}} \left( \nabla^2 - \frac{\omega (\omega + i \gamma_+)}{\epsilon_b} \epsilon_{\perp \pm} \right) \rho_\pm$$

and vice versa. An analytic solution of the resulting wave equation of fourth order can be found.

4. Conclusions

For solid particles, nonlocal interaction results in plasmon broadening and quenching [8]. This is also observed for the electrolyte. The typically observed blueshift of the plasmon resonance with respect to the local result is also found in the electrolyte system, but due to much larger wavelengths does not critically alter the classical resonance position. In the two-fluid model accounting for nonlocal charge interactions the positive charges take on the opposite oscillation direction and display inherent resonance structure that makes the nonlocal properties vanish faster than what is found for negative charges.

References

Surface waves with mixed exponential and linear localization characteristics

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Abstract

A theory underpinning new types of surface waves, guided by the planar interface of an anisotropic material and an isotropic material, has been developed. Unlike conventional surface waves, these new surface waves propagate only in one direction for each quadrant of the interface plane and their decay in the direction normal to the interface in the anisotropic partnering material is given by the exponent of an exponential function and a linear function of distance from the interface plane.

1. Introduction

The planar interface of two dissimilar linear materials can guide the propagation of surface waves whose characteristics depend upon the constitutive parameters of the partnering materials [1]. For example, (i) if one of the partnering materials is metallic and the other is dielectric, then the propagation of surface-plasmon-polariton (SPP) waves [2] is possible; and (ii) if both partnering materials are dielectric and at least one of them is anisotropic, then the propagation of Dyakonov surface waves [3, 4] is possible. Both SPP waves and Dyakonov surface waves propagate for a continuous range of directions in the interface plane. The angular existence domain of SPP waves encompasses all directions in the interface plane if both partnering materials are isotropic, whereas Dyakonov surface waves usually have much smaller angular existence domains. Furthermore, both SPP waves and Dyakonov surface waves decay exponentially with distance from the interface plane.

This paper concerns recently discovered special cases of SPP waves and Dyakonov surface waves. These are called SPP-Voigt waves [5] and Dyakonov–Voigt surface waves [6, 7]. As elaborated on in the next section, these surface waves arise when one of the partnering materials is anisotropic and the corresponding propagation matrix is non-diagonalizable. Both SPP–Voigt waves and Dyakonov–Voigt surface waves propagate only in one direction for each quadrant of the interface plane. Furthermore, the decay of both SPP–Voigt waves and Dyakonov–Voigt surface waves in the direction normal to the interface in the anisotropic partnering material is given by the product of an exponential function and a linear function of distance from the interface plane.

2. Theory

2.1. Preliminaries

Let us consider the canonical boundary-value problem for the simplest case that supports SPP–Voigt waves and Dyakonov–Voigt surface waves. That is, we consider the planar interface of (i) material $\mathcal{A}$ which is a uniaxial dielectric material, with relative permittivity dyadic $\varepsilon_{\mathcal{A}} = \varepsilon_{\mathcal{A}}^{\mathcal{I}} \mathbf{I} + (\varepsilon_{\mathcal{A}}^\mathcal{R} - \varepsilon_{\mathcal{A}}^{\mathcal{I}}) \mathbf{u}_x \mathbf{u}_x$, (1) that occupies the half-space $z > 0$; and (ii) material $\mathcal{B}$ which is an isotropic dielectric material, with relative permittivity dyadic $\varepsilon_{\mathcal{B}} = \varepsilon_{\mathcal{B}}^{\mathcal{R}} \mathbf{I}$, that occupies the half-space $z < 0$. The electromagnetic field phasors that characterize a surface wave that propagates at the angle $\psi \in [0, 2\pi)$ in the $xy$ plane are expressed for all $z \in (-\infty, \infty)$ as [1]

$$\begin{align*}
P(z) &= g(z) \exp \left[ i q (x \cos \psi + y \sin \psi) \right], \\
H(z) &= h(z) \exp \left[ i q (x \cos \psi + y \sin \psi) \right],
\end{align*}$$

(2)

wherein $q$ represents the surface wavenumber and the auxiliary phasors

$$\begin{align*}
g(z) &= e_x(z) \mathbf{u}_x + e_y(z) \mathbf{u}_y + e_z(z) \mathbf{u}_z, \\
h(z) &= h_x(z) \mathbf{u}_x + h_y(z) \mathbf{u}_y + h_z(z) \mathbf{u}_z,
\end{align*}$$

(3)

have complex-valued components, in general.

2.2. Half-space $z > 0$

The Maxwell curl postulates combined with the phasor representations (2), yield the $4 \times 4$ matrix ordinary differential equation [1]

$$\frac{d}{dz} \begin{bmatrix} f(z) \end{bmatrix} = i \begin{bmatrix} \mathcal{P}_{\mathcal{A}} \end{bmatrix} \cdot \begin{bmatrix} f(z) \end{bmatrix}, \quad z > 0,$$

(4)

wherein the column 4-vector

$$\begin{bmatrix} f(z) \end{bmatrix} = \begin{bmatrix} e_x(z) & e_y(z) & h_x(z) & h_y(z) \end{bmatrix}^T.$$

(5)

In the case of conventional SPP waves and conventional Dyakonov surface waves, the $4 \times 4$ propagation matrix $\begin{bmatrix} \mathcal{P}_{\mathcal{A}} \end{bmatrix}$ has four distinct eigenvalues, namely $\pm \alpha_{\mathcal{A}1}$ and $\pm \alpha_{\mathcal{A}2}$. Each eigenvalue has algebraic multiplicity 1 and geometric multiplicity 1. Let $\text{Im} \{\alpha_{\mathcal{A}1}\} > 0$ and $\text{Im} \{\alpha_{\mathcal{A}2}\} >$
0, in order to ensure that fields decay as \( z \to +\infty \). The general solution of the matrix differential eq. (4) is given as

\[
[f(z)] = [C_{A1} \mathbf{v}_A + C_{A2} (i \mathbf{v}_A + \mathbf{w}_A)] \exp (i \alpha_A z),
\]

where \( \mathbf{v}_A \) and \( \mathbf{w}_A \) are eigenvectors corresponding to the eigenvalues \( \alpha_{A1} \) and \( \alpha_{A2} \), respectively. The boundary conditions at \( z = 0 \) determine the constants \( C_{A1} \) and \( C_{A2} \).

In the case of SPP–Voigt waves and Dyakonov–Voigt surface waves, the propagation matrix \( \begin{bmatrix} \mathbf{P}_{A1} \mathbf{v}_A \end{bmatrix} \) has only two eigenvalues, namely \( \pm \alpha_A \). Each eigenvalue has algebraic multiplicity 2 and geometric multiplicity 1. Let \( \text{Im} \{ \alpha_A \} > 0 \), and let \( \mathbf{v}_A \) and \( \mathbf{w}_A \) denote an eigenvector and generalized eigenvector, respectively, corresponding to the eigenvalue \( \alpha_A \). Then the general solution of the matrix differential equation (4) is given as

\[
[f(z)] = [C_{A1} \mathbf{v}_A + C_{A2} (i \mathbf{v}_A + \mathbf{w}_A)] \exp (i \alpha_A z),
\]

with the constants \( C_{A1} \) and \( C_{A2} \) being determined by the boundary conditions.

2.3. Half-space \( z < 0 \)

The Maxwell curl postulates combined with the phasor representations (2), yield the the \( 4 \times 4 \) matrix ordinary differential equation [1]

\[
\frac{d}{dz} [f(z)] = i \begin{bmatrix} \mathbf{P}_{A2} \mathbf{v}_B \end{bmatrix} \cdot [f(z)], \quad z < 0.
\]

The \( 4 \times 4 \) propagation matrix \( \begin{bmatrix} \mathbf{P}_{A2} \mathbf{v}_B \end{bmatrix} \) has two eigenvalues, namely \( \pm i \alpha_B \). Each eigenvalue has algebraic multiplicity 2 and geometric multiplicity 2. Let \( \text{Im} \{ \alpha_B \} < 0 \), and let \( \mathbf{v}_B \) and \( \mathbf{w}_B \) denote the two independent eigenvectors corresponding to the eigenvalue \( \alpha_B \). The general solution of the matrix ordinary differential equation (8) is

\[
[f(z)] = (C_{B1} \mathbf{v}_B + C_{B2} \mathbf{v}_B) \exp (i \alpha_B z),
\]

with the constants \( C_{B1} \) and \( C_{B2} \) being determined by the boundary conditions at \( z = 0 \).

2.4. Dispersion equation

The tangential components of the electric and magnetic field phasors across the interface \( z = 0 \) must be continuous. Therefore

\[
[f(0^+)] = [f(0^-)].
\]

When eq. (10) is combined with the general solutions to the matrix ordinary differential equations (4) and (8), the following equation is delivered:

\[
\begin{bmatrix} \mathbf{Y} \end{bmatrix} \cdot \begin{bmatrix} C_{A1} & C_{A2} & C_{B1} & C_{B2} \end{bmatrix}^T = [\mathbf{0}].
\]

The \( 4 \times 4 \) characteristic matrix \( \begin{bmatrix} \mathbf{Y} \end{bmatrix} \) herein must be singular for surface-wave propagation [1]. Thus, the dispersion equation \( \begin{bmatrix} \mathbf{Y} \end{bmatrix} \neq 0 \) emerges.

3. Discussion

For the preceding descriptions of the propagation of SPP waves and Dyakonov surface waves, the dispersion equation is generally solved numerically for the surface wavenumber \( q \). In contrast, for SPP–Voigt waves and Dyakonov–Voigt surface waves, the dispersion equation is solved analytically for the surface wavenumber \( q \).

The analytic solutions reveal that SPP–Voigt waves and Dyakonov–Voigt surface waves propagate in a unique direction for each quadrant of the interface plane. Also, the analytic solutions deliver explicit constraints on the constitutive-parameter regimes for the partnering materials that support the propagation of SPP–Voigt waves [5] and Dyakonov–Voigt surface waves [6]. Once \( q \) is found, the phase speeds, propagation lengths, penetration depths and field profiles for the surface waves can be determined.

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References


Quantum spill-out induced enhancement in surface nonlinear plasmonic response

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Abstract

We develop a theoretical model based on the quantum hydrodynamic description of free-electrons and present its numerical implementation to investigate surface second-order nonlinearities. The presented method is capable of dealing with realistic profiles of equilibrium density of a metal. In the spectral analysis of Na and Ag thick slabs, we observe strong resonances induced by the electron spill-out from the metal surface. These resonances can be exploited to enhance the second-harmonic conversion efficiency by several orders of magnitude.

1. Introduction

Metals do not possess even-order intrinsic nonlinearities due to inherent centrosymmetry of their crystalline lattice. However, the complex dynamics of free-electrons provides a variety of mechanisms, which involve both the bulk and the surface regions, and can give rise to a second-harmonic generation (SHG) process. In particular, the harmonic generation process originating at the metal surface occurs within an angstrom-scale thin layer [1] where the induced charge density accumulates. At such near-atomic length scale nonlocal and quantum mechanical effects must be considered for an accurate description of electron dynamics.

Hydrodynamic theory in the Thomas-Fermi approximation (TFHT) has been widely employed to study linear and nonlinear properties of metal surfaces, however, it provides inaccurate results for the realistic (exponentially decaying) electron density profiles. The quantum hydrodynamic theory (QHT) has been shown to efficiently describe nonlocal and quantum effects in the linear approximation by adding a \( \nabla n \)-dependent kinetic energy correction to the TFHT and a very good agreement with the density functional theory calculations has been reported [2].

We expand, for the first time, the QHT equations beyond the linear approximation and present a numerical analysis of the SHG from Na and Ag films. We compute the equilibrium charge density self-consistently and show that the nonlinear QHT predicts spill-out induced strong resonance in the SHG efficiency spectra.

2. Theoretical framework

Considering that the fields can be written as a sum of harmonic contributions at \( \omega_1 \) and \( \omega_2 = 2 \omega_1 \) such that \( V(r,t) = V_1(r)e^{-i\omega_1 t} + V_2(r)e^{-i2\omega_1 t} + c.c., \) the nonlinear hydrodynamic equation [2] can be expressed as:

\[
-\frac{en_0}{m_e} \frac{\delta G}{\delta n} \bigg|_{j} = (\omega_j^2 + i\gamma \omega_j) P_j = \varepsilon_0 \omega_p^2 E_j + S_{j}^{nl}
\]

where \( \omega_p(r) = \sqrt{\frac{e^2 n_0(r)}{(m_e \varepsilon_0)}} \) is the space-dependent plasma frequency and the subscript \( j = 1, 2 \) denotes the field quantities at the fundamental and second harmonic, respectively. The parameter \( G \) representing the total internal energy of an electronic system can be approximated as \( G \approx T_F + \lambda_{W} T_W + E_{XC} \), where \( T_F[n] \) is the Thomas-Fermi kinetic energy functional, \( T_W[n, \nabla n] \) is von Weizsäcker correction term and \( E_{XC}[n] \) represents the exchange-correlation potential functional. The parameter \( \lambda_{W} \) defines decay of the electron density and it is usually taken as \( 1/9 \leq \lambda_{W} \leq 1 \). In Eq. (1), \( S_{1}^{nl} = 0 \) (undepleted pump approximation) and the nonlinear source \( S_{2}^{nl} \) is given by:

\[
S_{2}^{nl} = \frac{\delta n_1}{me} E_1 + i \omega_1 \frac{\mu_0 e}{me} P_1 \times H_1 + \frac{\omega_0^2}{en_0} P_1 : [\nabla P_1 + P_1 \nabla - P_1 \frac{\nabla n_0}{n_0}] + \\
+ \frac{en_1}{me} \frac{\delta G}{\delta n} \bigg|_{1} + \frac{en_0}{me} \frac{\delta G^{nl}}{\delta n} \bigg|_{2}
\]

Note that the term \( \nabla \nabla n_0/n_0 \) and the last two terms in Eq. (2) are the consequence of spatially-dependent electron density. Mathematical expressions for \( \frac{\delta G^{nl}}{\delta n} \) are explicitly reported in [2].

We numerically implement Eq. (2) within the jellium approximation in a commercial solver COMSOL Multiphysics and compute the equilibrium charge density self-consistently using the static QHT equation, given in [3].

3. Results and Discussion

We first consider a clean thick Na film to analyze the SHG under a TM-polarized plane wave excitation assuming different amount of electron spill-out from the metal surface, as shown in Fig. 1. We observe that for each value of the spill-out parameter \( \lambda_{W} \), the metal surface supports a strong resonance in the SHG efficiency spectra which is associated to the excitation of multipole surface plasmons in the linear response (not shown here).

The TFHT, on the other hand, does not show such feature neither in linear nor in nonlinear response as it neglects
the electron spill-out from the metal surface. The resonances appearing in Fig. 1b are consequence of spill-out of electron density from the metal surface.

In the case of a Ag film, the nonlinear QHT approximates well the angle-dependent experimental data taken from [4], as shown in Fig. 2a. To fit the data, we introduced a parameter $\alpha$ being the weight of nonlinear von Weizsäcker term, i.e., $T_{vW} = T_{vW}^0 + \alpha T_{vW}^{nl}$. In spectral SHG analysis of the Ag film, contrarily to the Na case, we could not see any resonance structure due to relatively lower spill-out and due to presence of the polarizable background in Ag.

We found that in this case the resonance in the SHG efficiency can still be excited if we enhance the electron spill-out at the Ag surface. A practical way to achieve this is by coating the Ag film with a thin dielectric layer (see inset of Fig. 2b); this reduces the work function at metal surface and increases the electron spill-out. As shown in Fig. 2b, the coated Ag film produces a large spill-out induced resonance which can be exploited to boost the SHG efficiency by several orders of magnitude.

4. Conclusions

Based on the quantum hydrodynamic description of electron dynamics, we presented a theoretical model to probe second-order nonlinearities in a plasmonic system. By using a self-consistent equilibrium charge density, we numerically investigated the SHG from a thick Na and Ag film. For Na, the nonlinear QHT predicted a very strong resonance in SHG efficiency due to electron spill-out. For a clean Ag film, however, we could not see such resonance due to much lower spill-out form Ag surface as compared to Na. Nonetheless, Ag films can also exhibit a strong resonance through the modification of their dielectric environment. This resonance can be used to boost the conversion efficiency by several orders of magnitude.

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References


Optical properties of a spatiotemporally modulated surface

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Abstract
In this research, we develop a differential formalism [1] in order to analytically calculate the optical response of spatiotemporal metasurfaces.

1. Introduction
Artificial fine structure on a surface enriches its optical response due to the diffraction on it. The optical properties of such structured surfaces are dominated by its geometry rather than the crystal structure, and they are sometimes called metasurfaces. One of the simple metasurfaces is a one-dimensional grating. Here, we investigate effect of temporal modulation on the grating (Figure 1). Besides the diffraction, there is the Doppler effect which further enriches the optical properties of the metasurfaces.

![Figure 1: Spatiotemporally modulated surface. The surface is sinusoidally modulated in space and time. The corrugation function is given by Eq. (1). We consider in-plane incidence of electromagnetic field and analyse the reflection and the transmission at the surface. The blue arrows are the tangential vectors of the surface \( \vec{t}(x,t) \), which is space and time dependent. The permittivities of medium and lower media are \( \varepsilon_\parallel \), respectively.

\[ s(x) = A \sin(\Omega t) \]  

(1)

Here, we have defined the strength \( A \), the spatial pitch \( 2\pi/y \), and the modulation frequency \( \Omega \) of the grating, respectively.

2. Differential formalism
We consider a grating-type boundary in which the corrugation of the surface is sinusoidal (see Figure 1),

\[ s(x) = A \sin(\Omega t) \]  

(1)

At the boundary between two dielectrics, the tangential components of the fields should be continuous,

\[ \begin{align*}
[\vec{t}_1 \cdot (\vec{H}_{inc} + \vec{H}_{ref} - \vec{E}_{tra})]_{z=s(x,t)} &= 0, \\
[\vec{t}_2 \cdot (\vec{H}_{inc} + \vec{H}_{ref} - \vec{E}_{tra})]_{z=s(x,t)} &= 0, \\
[\vec{t}_1 \cdot (\vec{E}_{inc} + \vec{E}_{ref} - \vec{E}_{tra})]_{z=s(x,t)} &= 0, \\
[\vec{t}_2 \cdot (\vec{E}_{inc} + \vec{E}_{ref} - \vec{E}_{tra})]_{z=s(x,t)} &= 0,
\end{align*} \]  

(10)

where \( \vec{t}_{1,2} \) are tangent vectors of the surface,

\[ \vec{t}_{1,2}(x,t) = \vec{u}_y - \frac{(\partial_x s)\vec{u}_x + \vec{u}_z}{\sqrt{1 + (\partial_x s)^2}}, \]

(11)

Those simultaneous equations (10) are space and time dependent, and we transform them into Fourier reciprocal
space. We assume the grating is ‘weak’ (i.e., $gA \ll 1$) and expand all the functions involved in the equations (10). After lengthy but straightforward algebra, up to the first order in the grating strength $gA$, Eqs. (10) lead to
\[
\begin{align*}
M_{> \leftarrow} - H_{\text{inc}} + M_{> \rightarrow} H_{\text{ref}} &= M_{< \leftarrow} H_{\text{tra}}, \\
N_{> \leftarrow} - H_{\text{inc}} + N_{> \rightarrow} H_{\text{ref}} &= N_{< \leftarrow} H_{\text{tra}},
\end{align*}
\]
for $p$ polarisation incidence, and
\[
\begin{align*}
\sqrt{\varepsilon} M_{> \leftarrow} - H_{\text{inc}} + \sqrt{\varepsilon} M_{> \rightarrow} H_{\text{ref}} &= \sqrt{\varepsilon} M_{< \leftarrow} H_{\text{tra}}, \\
\frac{1}{\sqrt{\varepsilon}} N_{> \leftarrow} - H_{\text{inc}} + \frac{1}{\sqrt{\varepsilon}} N_{> \rightarrow} H_{\text{ref}} &= \frac{1}{\sqrt{\varepsilon}} N_{< \leftarrow} H_{\text{tra}},
\end{align*}
\]
for $s$ polarisation incidence. Here, the elements of the vectors and the matrices, $H_{\text{inc,ref,tra}}$, $M_{\pm}$, and $N_{\pm}$, are
\[
\begin{align*}
(H_{\text{inc,ref,tra}})_{m} &= H_{\text{inc,ref,tra}}^{(m)}, \\
(M_{\pm})_{m} &= K^{(n)}_{\pm} \frac{\omega_{\pm} \varepsilon \varepsilon_{0}}{\omega_{\pm} \varepsilon \varepsilon_{0}} \delta_{m}^{(n)} + \frac{A}{2} K^{(n)}_{\pm} k^{(n)} \delta_{m+1}^{(n)} - \frac{A}{2} K^{(n)}_{\pm} k^{(n)} \delta_{m-1}^{(n)}, \\
(N_{\pm})_{m} &= \delta_{m}^{(n)} + \frac{A}{2} K^{(n)}_{\pm} \delta_{m+1}^{(n)} - \frac{A}{2} K^{(n)}_{\pm} \delta_{m-1}^{(n)},
\end{align*}
\]
where we have used $\delta_{m}^{(n)}$ is the Kronecker delta, and the superscript in brackets stands for the $n^{th}$ order quantity [e.g., $H_{\text{inc}}^{(m)} = H_{\text{inc}}(k + mg, \omega + m\Omega)$], where $m = -M, \cdots, -1, 0, +1, \cdots, +M$ corresponds to the diffraction order, and $M$ is cut off. The simultaneous equations for each polarisation contain $2 \times (2M + 1)$ unknown quantities, $H_{\text{ref,tra}}(k + mg, \omega + m\Omega)$. From the equations, we can calculate the reflection and the transmission coefficients,
\[
R_{\sigma}^{(m)} = \frac{H_{\text{ref}}^{(m)}}{H_{\text{inc}}^{(m)}}, \quad T_{\sigma}^{(m)} = \frac{H_{\text{tra}}^{(m)}}{H_{\text{inc}}^{(m)}} \quad (\sigma = p, s). \tag{14}
\]

3. Reflectance and transmittance

Energy flow of electromagnetic field is given by Poynting vector [2]. The average energy flow of the $n^{th}$ order field is
\[
\begin{align*}
\langle \mathbf{S} \rangle_{n} &= \frac{1}{2} \int \frac{dk \, dw}{2\pi 2\pi} \text{Re} \left( \frac{E^{(m)}(k, \omega)}{j} \times H^{(m)}(k, \omega) \right),
\end{align*}
\]
where the electric and magnetic field vectors are given in terms of the reflection and transmission coefficients (16). The reflectance (transmittance) is defined by the ratio of incident energy flow in the $-z$ direction to reflected (transmitted) one in the $+z$ ($-z$) direction,
\[
\begin{align*}
R_{\sigma}^{(m)} &= \frac{\mathbf{u}_{\sigma} \cdot \langle \mathbf{S} \rangle_{\text{ref}}}{\mathbf{u}_{\sigma} \cdot \mathbf{S}_{\text{inc}}}, \quad T_{\sigma}^{(m)} &= \frac{\mathbf{u}_{\sigma} \cdot \langle \mathbf{S} \rangle_{\text{tra}}}{\mathbf{u}_{\sigma} \cdot \mathbf{S}_{\text{inc}}} \quad (\sigma = p, s),
\end{align*}
\]
In Figure 2, the reflectance and transmittance spectra are shown. The $0^{th}$ order spectra are almost same as ones derived from the Fresnel coefficients. In the $\pm 1^{st}$ order spectra, we can observe singularities. Those are originally located at $\theta = 90^\circ$ but shifted by the diffraction.

4. Conclusions

We derived simultaneous equations, which determine the optical response of spatiotemporal metasurfaces, from the field continuities at the boundary with a differential formalism, and calculated the reflectance and transmittance. This work opens the way to analytical calculation of the optical properties of space-time-dependent systems.

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References

Wave scattering by layered structures in critical conditions

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Abstract

We use two-scale homogenization to derive an effective model governing the light scattering in structures alternating dielectric or metal/dielectric layers of subwavelength thicknesses. The procedure is conducted on the Maxwell equations in three dimensions; the resulting model involves effective constitutive relations which link the electric field and electric displacement and which supplant the conventional ones as well as non intuitive transmission conditions at the extremities of the substructure which replace the conventional ones. In transverse electric polarization, the model reduces to a fully local model and in transverse magnetic polarization, classical non local terms appear; the complexity of the structure is encapsulated in the non conventional transmission conditions. Comparison with direct numerics show that the model is accurate up to the critical conditions near total reflection.

1. Introduction

We present a generalization of the homogenization procedure presented in [1] for transverse electric polarized waves in a dielectric layered structure. It was shown that conducting this approach at the third order results in a fully local effective model, with an effective wave equation involving a permittivity frequency dependent and effective transmission conditions involving a parameter which depends only on the layer terminating the structure. Near the critical conditions of total internal reflection reported in [2], this model has been shown to capture the scattering properties of the actual structure with an accuracy less than 1\% up to $kd \sim 1$ (Fig. 1). Here, the procedure is performed on the Maxwell equations in three dimensions. The resulting model involves a generalized relation between the electric field $E$ and the electric displacement field $D$, revealing local and spatial dispersion of the effective medium. The transmission conditions between the effective medium and the surrounding media are in general non local well, in the sense where they involve tangential derivative of the fields. Expectedly, we recover the model of [1] in transverse electric polarization. For transverse magnetic polarization, the effective model reveals anisotropy and spatial dispersion by means of a fourth order spatial derivative of the magnetic field; it is also non local in the transmission condition.

2. The effective model

We start with the Maxwell equations in the dielectric (non magnetic) structure

$$\begin{align*}
\text{rot} H &= \partial_t D, \\
\text{rot} E &= -\partial_t H, \\
\text{div} D &= \text{div} H = 0, \quad \text{with } D = \varepsilon E,
\end{align*}$$

and $\varepsilon = 1$, $\varepsilon_x, \varepsilon_y$ is a function of $z$. The effective model aims to describe the fields $(E, D, H)$ in an average sense which results in (a) an effective medium for $z > 0$ being homogeneous, anisotropic and possibly non local and (b) effective transmission conditions which in general differ from the usual continuities of $H$, of the normal component of $D$ and of the tangential component of $E$. The model is a generalization of that in [1] which hold for transverse electric polarized waves (with $E(x,z)$ polarized along $e_y$). Below we report the resulting model in the harmonic regime (with time dependence $e^{-i\omega t}$ in the air where we set the velocity to unity, and $k = \omega$ is the wavenumber).

$$\begin{align*}
\text{rot} H &= -iD, \\
\text{rot} E &= iH, \\
\text{div} D &= \text{div} H = 0
\end{align*}$$

(2)

with, for $z < 0 \ E = D$ and for $z > 0$

$$E = \begin{pmatrix}
\varepsilon^{-1}_1(k) - \alpha \partial_{xx} & -\alpha \partial_{xy} & 0 \\
-\alpha \partial_{yx} & \varepsilon^{-1}_1(k) - \alpha \partial_{yy} & 0 \\
\beta \partial_{xz} & \beta \partial_{yz} & \varepsilon^{-1}_1(k)
\end{pmatrix} D
$$

(3)

where $(\alpha, \beta)$ are non dimensional constant parameters which depend on the structure of the multilayer. Next, the usual transmission conditions read as $[H] = [E_z] = [E_y] = [D_z] = 0$ are replaced by effective transmission
conditions of the form

\[
\begin{align*}
[H] &= -ia k e_z \times \mathbf{E}, \\
[E_x] &= b \partial_z D_z, \\
[E_y] &= b \partial_y D_z, \\
[D_z] &= a (\partial_x E_x + \partial_y E_y),
\end{align*}
\]

(4)

where \((a, b)\) are constant parameters which depend only on the arrangement of the layer terminating the structure (at \(z = 0\) and at \(z = \ell\)). In the above relation, for a field \(F(x, y, z)\) being discontinuous, say at \(z = 0\), we defined \(\mathbf{T} = \frac{1}{2} (F(x, y, 0^+) + F(x, y, 0^-))\).

- The case of TE polarized waves: If we consider \(D\) and \(E = E(x, z) e_y\) along \(e_y\) (hence \(H_y = 0\)), then (2) reduces to a 2D problem in \((x, z)\); accounting for (4) and for the transmission conditions (3), the problem reads

\[
\begin{align*}
(\partial_{xx} + \partial_{zz}) E + \varepsilon_0 (k) k^2 E &= 0, \\
[E] &= 0, \\
[\partial_z E] &= a k^2 E.
\end{align*}
\]

(5)

- For TM polarized waves, \(H = H(x, z) e_y\) and where \(E_y = 0, (2), (3)\) and (4) simplify to

\[
\begin{align*}
\varepsilon_0^{-1}(k) \partial_{xx} H + \varepsilon_0^{-1}(k) \partial_{zz} H - \gamma \partial_{xzz} H + k^2 H &= 0, \\
[H] &= -a (ik E_x), \\
[i k E_x] &= -b \partial_{xx} H,
\end{align*}
\]

(6)

with \(\gamma = (\alpha + \beta)\) and \(ik E_x = \partial_x H\) for \(z < 0\) and \(ik E_x = (\varepsilon_0^{-1}(k) - \alpha \partial_{xx}) \partial_x H\) for \(z > 0\).

### 3. Numerical validation of the effective model

We inspect the scattering properties of the actual structures in the case of all dielectric layers \((\varepsilon_a > 0, \varepsilon_b > 0)\) and in that of metal-dielectric succession \((\varepsilon_a < 0, \varepsilon_b > 0)\). The solution of the actual problem is calculated numerically and it is compared to that given by the effective model which is given in a close form. We report in Fig. 2 the transmission at moderate \(kd = 0.5\) value for the succession of layers considered in [1, 2]. The anomalous is visible with different scattering for the direct order (a structure starting with a layer \(a\)) and the inverse order (starting with a layer \(b\)); as a result, the classical EMA fails in capturing this sensitivity to the layer arrangement (dotted grey lines). In comparison, our effective model is 0.1% accurate in both cases (additional results can be found in [1]).

We report in Fig. 3 an additional and interesting result coming from [3]; in this reference, a model based on the transmission through a metal-dielectric structure is analyzed through an operator effective medium theory involving electric dipoles, chirality and magnetic and electric quadrupoles. In the case \(kd = 2\), that is when thickness \(d\) is not much less than the incident wavelength. The authors remark that their model is not very accurate but it catches the resonances of the exact solution. They conclude that other homogenization models considered cannot be used at all outside their applicability ranges. What we show in Fig. 3 is that our model has exactly the same accuracy as the operator effective model of [3] which suggests an equivalence between both models, which is not immediate to establish.

![Figure 2: Transmission against sin θ for all dielectric structures the case reported in [2], \(\varepsilon_a = 4, \varepsilon_{ad} = 3, \varepsilon_s = 5, \varepsilon_b = 1, d_a = d_b\), and \(kd = 0.5, N = 20\); direct (left) and inverse (right) order. Direct numerics (plain black lines) and effective model (dotted blue lines).](image)

![Figure 3: Transmission against sin θ for metal-dielectric structure, as reported in [3], \(\varepsilon_a = 1, \varepsilon_{ad} = 0.215, \varepsilon_s = -3, \varepsilon_b = 2.25, d_a = d_b\) and \(kd = 2, N = 10\); same representation as in Fig. 2.](image)

### References


A (re-)introduction to spatial dispersion

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Abstract
I examine the traditional approach to spatial dispersion, and contrast this with an alternative based on a fundamental re-examination of the basic principles. I emphasise the key role of the spatial properties which generate spatially dispersive behaviour: geometry, structure, and dynamics.

1. Introduction
Spatial dispersion is distinct from temporal dispersion, and is usually described as a non-local dependence of material properties on both direction and wavelength. It is of particular interest in electromagnetic systems involving metamaterials, due to their underlying spatial structure; but it also is relevant to acoustic and elastic metamaterial systems. It has been long observable in crystals [1], being particularly of importance where the propagation wavelength becomes comparable to the lattice parameters (see e.g. [2]). Further, it is also significant in the region of the material resonances utilized in metamaterial unit cells, where constitutive parameters such as the permittivity and permeability – and likewise their acoustic or elastic counterparts – are maximised or have near-zero local values [3] or where the response is non-reciprocal [4].

Spatial dispersion usually appears as a either spatially non-local effect that produces a wavevector dependence of the material parameters, or as a non-trivial wavevector dependence for the dispersion relations. Although spatial dispersion can be modelled to suit intuition or an empirical fit to some data, it is preferable to be more systematic. There can be, for example, debate as to whether in any given approximation the \( k \) dependence should appear as a numerator or a denominator. The approach here is to start with a “microscopic” view of a system, and use that to motivate the appropriate origin and functional form for a spatially dispersive dispersion relation.

2. Discussion
In this presentation I will first give an overview of the traditional approaches; discussing the starting points and its consequences, such as the view (e.g. [5]) that spatial dispersion due to (non-trivial) wavevector-dependence in the dispersion relations, can be categorized into two cases ‘weak’ spatial dispersion, where the spatial effects have been approximated as a local effect; and ‘strong’ spatial dispersion, where nonlocal effects remain important [6, 7].

I will then challenge this traditional approach by describing three physically distinct ways that spatial dispersion can arise [8], briefly describing examples of each; a viewpoint is grounded in the following assertion:

**Spatial dispersion refers to any dispersive behaviour that occurs (solely) as a result of specified spatial properties.**

Each of these mechanisms has (a) no time dependence beyond that required to support a wave, and (b) a specification of time-independent material properties. The lack of any (non-trivial) time dependence ensures that the phenomena treated here are entirely unrelated to the more commonly considered topic of temporal dispersion. The first two spatial dispersion mechanisms depend entirely on spatial properties, whereas the third derives from a coupling to a dynamic medium, leading to a changed wave velocity and/or an “effective mass” term.

3. Summary
The main focus will be on spatial dispersion in electromagnetic systems or artificial functional media such as metamaterials, but the distinctions apply equally well to waves in acoustic or elastic materials, or indeed potentially any material system which supports wave propagation of some kind. Note that the idea of spatial dispersion as being grounded in spatial properties as opposed to (spectral) wavevector ones is mirrored in the various treatments of temporal dispersion: although sometimes seen as a consequence of a dynamic time-domain process [9] particularly when implemented in FDTD algorithms [10], temporal dispersion is more often discussed in solely terms of a (spectral) frequency response [11, 12].

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Twisted light in metamaterials with spatial dispersion

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Abstract

We report on the theoretical studies of generation of non-classical light carrying orbital angular momentum and its propagation in metamaterials with spatial dispersion. The distinctive feature of such a light is a longitudinal component of the field, the effect of which increases the degree of its twisting. It leads to arousing additional electromagnetic excitations in spatially dispersive media. As a mechanism of generation of such a waves we consider well-known Cherenkov radiation generated by relativistic charged particles, which has its own special features in metamaterials due to its strong nonlocal spatial response. We also discuss the role of relativistic effects and causality principle in terms of the phenomena considered.

Plane wave describing free electromagnetic field in vacuum is well known to be usually considered as transversal. Yet, beyond the tenets of conventional conceptions, the propagating fields can contain longitudinal components, and not only in a matter but in vacuum as well. For example, the twisted light – the light carrying orbital angular momentum, i.e. having nonzero projection of the orbital angular momentum on the propagation direction – is not only capable of being described as a partially longitudinal, but even must be, at least beyond paraxial approximation, as was shown recently by Quinteiro with coauthors [1]. In the processes of light – matter interaction it is important as the material receives the orbital momentum from twisted photons [2] which influences its response. These photons are a special case of the so-called non-classical light, which also includes quantum superpositions such as the "Schroedinger's cat", Airy beams and other states of photons, Wigner functions of which are not completely positive. The driving force of these studies is not only the academic interest to the problems of classical /quantum electrodynamics related to this under-investigated degree of freedom of electromagnetic radiation, but also the search for the new tools of the study of physical phenomena, new applied research methods and the development of new technologies, including micro- and nano-manipulation. This studied both theoretically and experimentally [3-7] in the last quarter of the century since the pioneering publication [8].

On the other hand, metamaterials are known to demonstrate strong nonlocal dispersion, both frequency and spatial ones [9-11]. The term “spatial dispersion” was used for the first time, probably, by Gerzsensttein [12], and since then this phenomenon has been proved to play a key role in many and many fields [11, 13, 14], leading to a variety of new types of electromagnetic waves in media. What is significant is that the spatial dispersion is of primary importance for any longitudinal excitations in media. Moreover, it proves that the spatial dispersion is absolutely fundamental phenomenon, which is necessary, for instance, for the high temperature superconductivity to exist (the condition must be satisfied) [15]. The spatial dispersion plays a vital part in violation of the Kramers-Kronig relations [15], which are, in a sense, even more fundamental than basic Maxwell’s equations, because they are caused directly by the causality principle. For the moment of works of Kirzhnits [15] the metamaterials was not known so widely; still, the application of causality principle can be used in case of metamaterials but with reservations [16].

In this report we consider the propagation of non-classical light carrying orbital angular momentum and its propagation in metamaterials with spatial dispersion. The distinctive feature of such a light is a longitudinal component of the field, the effect of which increases the degree of its twisting, i.e. with the projection of the orbital angular momentum on the propagation direction. It leads to arousing additional electromagnetic excitations in spatially dispersive media. As a mechanism of generation of such a waves we consider well-known Cherenkov radiation generated by relativistic charged particles, which has its own special features in metamaterials due to its strong nonlocal spatial response. We also discuss the role of relativistic effects [17, 18], effect of coupling between constituent meta-particles [19] and causality principle in terms of the phenomena considered.

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Analysis of nonlocal constitutive relations to homogenize metamaterials

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Abstract

To homogenize metamaterials, it has been appreciated only recently that nonlocal constitutive relations are more performant than local constitutive relations. This implies that the response at the effective level does resemble much closer the response of the actual metamaterial, i.e. the response at the mesoscopic level, when nonlocal constitutive relations are considered. These nonlocal material laws are obtained by approximating a general response function of the electric field describing the response of the metamaterial. To this end, several approximation methods can be used as the exact response function cannot be handled. In the present research, a second order Padé approximation of the response function is adopted. Several formulations can be derived. To decide which formulation is consistent for the homogenization, we present a checklist each constitutive relation has to pass to be physically and mathematically admissible for this purpose.

1. Introduction

Metamaterials (MMs) allow to control the propagation of light in a way inaccessible with natural materials [1, 2]. These artificial materials are made from sub-wavelength inclusions. These inclusions are also called meta-atoms and they are mostly arranged in a periodic manner to turn them into an actual material. The periodic arrangement of these inclusions allows to homogenize MMs and to discuss their properties at the effective level. How such homogenization has to be done was always a prime mathematical challenge [3].

Mostly, local constitutive relations have been considered [4]. This assumption is equivalent to saying that the MM possesses a weak spatial dispersion (WSD). The WSD proved its efficiency when the period of the meta-atoms’ arrangement is much smaller than the wavelength of light. However, this is not the case for actual MMs where the period and the operational wavelength are in the same order of magnitude. Then, the optical response of the MM cannot be explained using local constitutive relation. It has to be stressed that it is not just a problem of finding the actual material parameters, but the problem is rather to find an appropriate constitutive relation to characterise the MM at the effective level.

Therefore, as an alternative path, nonlocal constitutive relations are currently explored that lead to Maxwell’s equations of higher order. They provide generally a much better description for the propagation of light in MMs. This assumption of nonlocality is equivalent to saying that the MM possesses a strong spatial dispersion (SSD) [5].

A general nonlocal response function cannot be handled practically, because particularly it cannot be evaluated near interfaces. Therefore, it has to be approximated to make practical use of it. While a Taylor approximation has been considered for this purpose that is truncated after a few terms [6], we consider here a Padé approximation.

But there is not a unique way to perform this Padé approximation; but indeed multiple formulations can be found at the same level of approximation. To be specific, when approximating the nonlocal response function with a second order Padé rational function, nine different formulations for the constitutive relation can be found. It is the purpose of this contribution to identify a checklist each of these possible constitutive relations has to pass in order to be considered as valid. We show that only two out of the obtained nine Padé approximations pass the checklist. This checklist of course is applicable beyond the specific cases studied in here and has with that a general value for the future exploration of MMs. Details of this work were published in Ref. [7].

2. Homogeneous metamaterials

In the spatial-frequency space, the most general nonlocal constitutive relation we are considering can be written as

$$\hat{D}(\omega, \mathbf{k}) = \hat{R}(\omega, \mathbf{k})\hat{E}(\omega, \mathbf{k}).$$  (1)

For centro-symmetric MMs, a rational approximation of the response function, i.e., of Padé-type, leads to a nonlocal material law in the form of a differential equation in the real space. The wave equation we can obtain finally results
\[ \nabla \times \nabla \times \mathbf{E}(\omega, \mathbf{r}) = k_0^2 \varepsilon(\omega) \mathbf{E}(\omega, \mathbf{r}) \\
+ \left[ k_0^2 \mathbf{p}(\omega, i \nabla) + \mathbf{q}(\omega, i \nabla) (\nabla \times \nabla \times \mathbf{E}) \right]. \] (2)

Here, \( \mathbf{p}(\omega, i \nabla) \) and \( \mathbf{q}(\omega, i \nabla) \) are differential operators that may take one of the following forms

\[ \zeta(\omega) \nabla \times \nabla \times, \quad \nabla \times \zeta(\omega) \nabla \times, \quad \nabla \times \nabla \times \zeta(\omega), \] (3)

such that \( \varepsilon(\omega), \zeta(\omega) \in \mathbb{C}^{3 \times 3} \) are assumed to be anisotropic diagonal matrices. They represent the effective material parameters. Notice that \( \zeta(\omega) \) is different for \( \mathbf{p}(\omega, i \nabla) \) and \( \mathbf{q}(\omega, i \nabla) \). Hence, the nonlocal wave Eq.(2) arises in nine different formulations that model the propagation of light in a homogeneous MM.

When considering local constitutive relations, such that for a given transverse wave vector components and frequency, only a single forward propagating mode is resulting [6]. In contrast, the solutions of the dispersion relation for nonlocal materials reveal that we have multiple propagating modes. To fix the amplitudes of these propagating modes at an interface, we need additional interface conditions that we can derive by means of weak formulations.

3. Selection criteria

To give a precise answer about which wave equation describes in a better way the propagation of light in homogeneous MMs, we present mathematical and physical criteria that intervene basically in the checking process. The checklist we propose contains three criteria. First, we require that the number of unknown field amplitudes that is defined through the dispersion relations is matched with the number of interface conditions derived at the interface between the MM and an ordinary material, e.g., vacuum. Second, we know implicitly that the local approach is always contained in the nonlocal approach when taking the limit of the nonlocal parameters to zero. Then, we have to analyse the resulting interface conditions according to this principle. More precisely, they have to result to the same as the interface conditions resulting when following the WSD approach. This fact directly influences the reflection and transmission coefficients obtained through the Fresnel formulas using the interface conditions. The third criterion consists in checking the conformity with the Casimir-Onsager reciprocity principle. This principle imposes some symmetry conditions on the nonlocal response function \( R(\omega, k) \). Finally, it turns out that the only constitutive relations passing the checklist are

(a) the one that leads to a wave equation in which the material parameters are written between an equal number of curl operators, written as

\[ \nabla \times \nabla \times \mathbf{E} = k_0^2 \varepsilon(\omega) \mathbf{E} + k_0^2 \alpha \nabla \times \mathbf{E} \\
+ \nabla \times \nabla \times \mathbf{E}. \] (4)

(b) the equation given by

\[ \nabla \times \nabla \times \mathbf{E} = k_0^2 \varepsilon(\omega) \mathbf{E} + k_0^2 \alpha \nabla \times \nabla \times \mathbf{E} \\
+ \nabla \times \nabla \times \mathbf{E}, \] (5)

with the additional restriction that \( \alpha \) is a scalar.

4. Conclusion

Approximating the nonlocal response function by means of a Padé-type approximation allowed us to derive several formulations modelling the light-matter interaction. The analysis of each resulting formulation enabled us to set a solid background that can be used for studying and checking the validity of other models, not necessarily obtained by following this approach.

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References

Refraction and Impedance Patterns in Moving Media

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Abstract

To study wave propagation in moving media, a common graphical tool is the isofrequency diagram, or refractive index pattern, which provides the direction and the velocity of a wave. Here, we complement this tool with the impedance pattern, which provides information on the wave amplitude. We argue that the two tools should be used on an equal footing when solving problems involving moving media.

1. Introduction

There is a great abundance of studies on wave propagation in moving media. One of the earliest works is that of H. Fizeau, who measured the velocity of light travelling through flowing water in 1851 [1]. Later, H. Minkowski applied special relativity concepts to study waves in moving media [2]. More recently, there have been works on propagation in non-uniform velocity, such as propagation in vortex flows [3]. There have also been many works on the scattering of waves from bounded moving media, i.e. [4, 5].

A common tool to study the wave velocity and direction is the isofrequency diagram, or refractive index pattern [6]. This diagram provides information on the phase velocity, \( v_p = \omega / k \), and group velocity, \( v_g = \nabla_k \omega \) of the wave. However this diagram does not provide any information on the wave amplitude. We suggest that an impedance pattern should always be plotted in parallel with the refractive index pattern to include that missing information.

In this paper, we recall the refractive index pattern of moving media, and then present the impedance pattern, and show how these vary as the velocity increases.

2. Refractive Index Pattern

The refractive index of a moving isotropic dielectric with refractive index \( n' \) moving at a velocity \( v \) in direction \( \theta_k = 0^\circ \) with respect to the laboratory frame is expressed in the polar coordinate system \((n, \theta_k)\), with \( \theta_k \) the angle of the wavenumber, as [7]

\[
\frac{(n \cos \theta_k - \chi)^2}{n'^2 \alpha^2} + \frac{n^2 \sin^2 \theta_k}{n'^2} = 1, \tag{1a}
\]

where

\[
\chi = \beta \frac{1 - n'^2}{1 - \beta n'^2}, \quad \alpha = \frac{1 - \beta^2}{1 - \beta^2 n'^2}, \tag{1b}
\]

which is the equation of an ellipse, off-centered by \( \chi \), with semi-major axis \( n' \alpha \) and semi-minor axis \( n' \), with \( \beta = v/c \) the normalized velocity.

Figure 1 plots \( n/n' \) and phase velocity \( v_p/c = 1/n \). Figure 1(a) plots the subluminal motion, \( v < c/n' \). The curve of the refractive index is an ellipse, and the curve of the phase velocity is a parabola. Figure 1(b) plots the case where the motion approaches the speed of light in the medium, \( v \to c/n' \). In this case, the refractive index ellipse flattens out, approaching a parabola, and the phase velocity limaçon curve becomes a cardioid, with a cusp where \( v_p \to 0 \) for “upstream” propagation.
3. Impedance Pattern

We now plot the corresponding impedance pattern. This may be obtained from the constitutive relations of a moving medium and Maxwell equations, and reads

\[
\frac{\eta'^2 \cos^2 \theta_S}{\eta'^2} + \frac{\eta'^2 \sin^2 \theta_S}{\eta'^2} = 1, \tag{2}
\]

where \(\eta'\) is the wave impedance of the medium in its rest frame. Eq. (2) is an ellipse centered at the origin of the polar coordinate system \((\eta, \theta_S)\). Note that the impedance is expressed in terms of the angle \(\theta_S\), which is the angle of the Poynting vector \(S = E \times H\), while the refractive index is expressed in terms of the angle \(\theta_k\), which is the angle of the wavenumber. These are not equal in anisotropic media.

We note from (2) that for propagation parallel or antiparallel to the dielectric motion \((\theta_S = 0^\circ \text{ or } \theta_S = 180^\circ))\), we have \(\eta = \eta'\), and therefore the impedance is independent of the direction of the medium velocity.

Figure 2 plots (2), along with the admittance curve \(\zeta / \zeta' = \eta / \eta'\). Figure 2(a) plots the subluminal case \((v < c/n')\). The impedance increases for increasing obliqueness, and is maximal for perpendicular propagation \((\theta_S = 90^\circ)\). The symmetry of the curve indicates that up- and down-stream impedances are equal. Fig. 2(b) plots the limit of the subluminal case \(v \to c/n'\). The ellipse becomes very elongated, and the admittance is seen to tend towards 0 for perpendicular propagation.

4. Conclusion

Although it is usually omitted, the impedance pattern of moving media is useful for determining wave propagation phenomena. We showed that for a moving isotropic dielectric medium, the impedance’s anisotropy is elliptical, with the semi-minor and semi-major axes swapped with respect to the refractive index pattern, and the curve is symmetric. This graphical representation will be useful for the calculation of scattering from moving media, and should be systematically used for solving spacetime problems.

References


D and H cannot exist: Axions, topology and global charge conservation

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Abstract

The excitation fields D and H cannot be directly measured and have a gauge freedom. Admitting this freedom opens many possibilities, concerning the axionic response, which have direct application. We show a simple scenario which due to topological reasons is impossible using D and H. It can be used to model periodic lattices which have non zero total charge and show that an evaporated black hold can break charge conservation. We reflect on the nature of a homogeneous axionic response.

1. Introduction

There is debate in the literature as to whether D and H are really physical fields which can be directly measured or simply a potential for the charge and current. This contrasts with the electromagnetic fields E and B, where the integrated fields can be measured inside a material using the Aharonov-Bohm effect.

It is easy to see that Maxwell’s equations are invariant if we add a gauge (φg, Ag) to the excitation fields D → D + ∇ × Ag and H → Ag + ∇φg. As a simple example the H-field in a permanent magnet can either be parallel or anti-parallel to the B-field depending on the choice of constitutive model used[1].

In [3] a minimal extension to Maxwell’s equations is proposed which eliminated (D, H), via the use of first order operators on vectors. It is shown that this gives rise to 20 new parameters to describe the medium. Of these four (ζ, ζt) describe an axion field. Thus the simplest example which extends Maxwell’s equations is given by a permittivity ε and permeability μ as

\[ \nabla \cdot B = 0, \nabla \times E + \dot{B} = 0, \nabla \cdot (\varepsilon E) - \nabla \cdot B = \rho \]

and

\[ \nabla \times (\mu^{-1} B) - \varepsilon \dot{E} + \nabla \times E + \nabla \times \dot{B} = J \] (1)

where for conservation of charge

\[ 0 = \dot{\rho} + \nabla \cdot J = (\nabla \times \nabla \cdot E) + \left( \nabla \nabla \cdot E - \nabla \nabla \cdot \zeta \right) \cdot B. \] (2)

This can be easily achieved if (ζ, ζt) satisfy

\[ \nabla \times \nabla \cdot \zeta = 0 \quad \text{and} \quad \nabla \times \zeta - \zeta_t = 0. \] (3)

One can easily observe that we can obtain (1) and (3) by using standard macroscopic Maxwell where

\[ D = \varepsilon E - \kappa_{ax} B \quad \text{and} \quad H = \mu^{-1} B + \kappa_{ax} E \] (4)

where \( \kappa_{ax} \) is an axionic response scalar field and \( \zeta = \nabla \kappa_{ax} \) and \( \zeta_t = \kappa_{ax} \). However there are some very important cases when we cannot apply (4), either because there are topological reasons why \( \kappa_{ax} \) does not exist or because we are questioning what we mean by a homogeneous axionic field.

2. Topological reasons to use axionic media

Outside a conducting cylinder. An example that can be built consists of conducting metal cylinder, charged to create a purely radial electric field (E)r and then surrounded by an array of parallel wires used to implement the axionic response. See figure 1, then for a cylinder of radius \( r = r_0 \), in this static case we can set

\[ \zeta = \frac{Z_0}{r} \theta \quad \text{and} \quad \zeta_t = 0 \] (5)

where \( Z_0 \) is a constant, figure 2. A crucial point that separates our axionic medium (1) from the standard constitutive relations is that in this situation \( \zeta \) cannot be the gradient of any field \( \kappa_{ax} \) as in (4); thus the standard constitutive relations cannot describe this. Although locally we can set \( \kappa_{ax} = Z_0 \theta \), globally \( \theta \) is not single valued and continuous;
3. Homogeneous axion fields

The other case when one cannot simply apply (4) is when considering homogeneous axion fields. In standard Maxwell, if $\kappa_{ax}$ is constant, then it has no effect, except at the boundaries of the axionic material. By contrast in our medium, it is $(\zeta, \zeta_t)$ which are constant. This leads to an inhomogeneous $\kappa_{ax}$, i.e., $\kappa_{ax} = t\zeta + x\zeta_x + y\zeta_y + z\zeta_z$. Here $t$ is time, $(x, y, z)$ are the usual Cartesian coordinates, and $(\zeta_x, \zeta_y, \zeta_z, \zeta_t)$ are the 4 axionic material constants. If we do make $\kappa_{ax}$ constant then $\zeta = 0$ and $\zeta_t = 0$. Thus, for a block of material in which $\kappa_{ax}$ is constant, the traditional axionic terms $\zeta$ will only appear on the surface of the material. We examine a cylindrical system with a homogeneous axionic medium, which otherwise would require an arbitrarily large $\kappa_{ax}$.

4. Conclusion

We presented a minimal extension to the standard constitutive relations for Maxwell's equations, and have achieved this by combining the Maxwell-Ampere equation with the constitutive properties of an electromagnetic medium. Thus we eliminate the need for the excitation fields $(\mathbf{D}, \mathbf{H})$. This has direct application. We propose a simple scenario using fields around a cylinder, the homogenisation of which is easy using our approach but impossible using the standard Maxwell's equations. We show that our approach can be used in periodic lattice calculations where the total charge is non-zero, again impossible using standard Maxwell. We show the implications for the concept of a homogeneous axionic field. In a more exotic application, a black-hole that forms and then completely evaporates, breaks global charge conservation.

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References

Boundary Conditions in Time Dependent Materials

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Abstract

Currently there is growing interest in time dependent media, materials whose constitutive relations change with time. Most models assume the permittivity and permeability are constant. This approach works if both permittivity and permeability are real. However to model lossy media it is natural to consider complex constitutive relations. In this paper we demonstrate with a simple example that such a model is unrealistic in a time dependent medium. Furthermore we derive the correct boundary conditions necessary for wave propagation in a time dependent medium.

1. Introduction

Early work in the area of time-dependent media by Morgen-thaler [1] considered the case where the permittivity varied sinusoidally in time (but always positive). Demonstrating for a propagating wave a time dependent permittivity produces both forward and backward propagating waves. More recently the authors of [2] theoretically considered an Instantaneous Time Mirror where the permittivity changes from real, $\varepsilon > 0$ at a time $t_0$ to real, $\varepsilon < 0$, causing amplification of the wave. Although for time-dependent media this constant permittivity/permeability model is appropriate only if both are real. To model loss it is natural to consider complex constitutive relations. However a simple example presented in this paper demonstrates that such a model is unphysical.

2. Constant Complex Permittivity

In our example consider a wave propagating in an infinite media where the constitutive relations at time $t_0$ changes from ($\varepsilon^- \in \mathbb{R}$) to a material with constant permittivity ($\varepsilon^+ \in \mathbb{C}$) and dampened wave propagation ($\Im(\varepsilon^+) > 0$), whilst the permeability remains unchanged ($\mu = \mu_0$). For $t < t_0$ wave propagation is of the form,

$$D(t, z) = D_0 \cos(\omega^- t - k^- z) \hat{x}$$

where $D_0 \in \mathbb{C}$ is the EM amplitude, and $\omega^-, k^-$ are both real and positive and satisfy the vacuum dispersion relation $(k^-)^2 = \varepsilon_0 \mu_0 (\omega^-)^2$. In this case the general solution, when $t > t_0$, is given by;

$$D(t, z) = \left( a_+ e^{-i\omega^+ t + ik^+ z} + a_- e^{-i\omega^+ t - ik^+ z} \right) \hat{x}$$

with the dispersion relation $(k^+)^2 = \varepsilon^+ \mu_0 (\omega^+)^2$. Solving equations (1) and (2) at the time boundary, we see that $k^+ = k^-$, with four unknowns. The refractive index takes the form $n^+ = \sqrt{\varepsilon^+ \mu_0}$, as both roots are included in equation (2) the root we choose for $n^+$ is unimportant. Defining $c = (n^+)^{-1}$, we choose the root of $n^+$ where $\Re(c) = c_k > 0$ and $\Im(c) = c_l < 0$, this means equation(2) becomes,

$$D(t, z) = \left( a_+ e^{ik^+ (\tau_0 t - \omega^+ z)} e^{ik^+ c_l t} + a_- e^{ik^+ (\tau_0 t + \omega^+ z)} e^{ik^+ c_l t} \right) \hat{x}$$

Since $k^+ = k^- > 0$ and $c_l < 0$ then the last two terms of equation (3) must blow up, meaning the constant permittivity model is non-physical for a material with time dependent constitutive relations.

3. Temporal Boundary Conditions

Consider an infinite medium where the permittivity changes from $\varepsilon^- \leftrightarrow \varepsilon^+$ throughout the whole medium at time $t_0$. At the microscopic level the sudden change in permittivity results in an “instantaneous” movement of the electrons, which creates a bound instantaneous dipole current ($J$), meaning the total current ($\bar{J}$) in the medium is,

$$\bar{J} = J_{\text{reg}} - \delta(t - t_0) J$$

where $J_{\text{reg}}$ is the regular current from Maxwells equations. For the temporal case considered in this paper each of the terms in Maxwell’s equations,

$$\nabla \cdot B = 0, \quad \nabla \cdot D = \rho, \quad \nabla \times E + \partial_t B = 0$$

$$\nabla \times H - \partial_t D = J,$$

are defined in terms of a state before the time boundary $t_0^-$ and a state after the time boundary $t_0^+$, this means, for example, the displacement field $D$, and the magnetising field $H$, can be defined in terms of $D$ ($H$) before and after the boundary using the Heaviside function $\theta(t - t_0)$,

$$D = \theta(t_0^- - t) D(t_0^+, x) + \theta(t - t_0) D(t_0^-, x)$$

$$H = \theta(t_0^- - t) H(t_0^+, x) + \theta(t - t_0) H(t_0^-, x)$$
At the time boundary \( t = t_0 \) and \( J_{reg} = 0 \), using eqns (6) and (4) in the forth of Maxwells equations (5) we find for \( D \) (and similiar for \( B \))

\[
[D] = \mathcal{J} \quad \text{and} \quad [B] = 0 \tag{7}
\]

where \([D] = D(t_0^+, x) - D(t_0^-, x)\) is the difference between the value of \( D \) before and after the boundary. Hence equation (7) defines the temporal boundary conditions. In this form the boundary conditions ensure the continuity of \( D \) (\( B \)) and \( E \) (\( H \)) across the time boundary. Using these boundary conditions with equations (1) and (2) also yields the same result as equation (3).

We have shown it is not possible to implement a time boundary with a constant complex refractive index, it is necessary for \( \bar{n}(\omega) \) to be dispersive. As an example we consider a general constitutive relationship for \( t > t_0 \), using one or more Lorentz oscillators, where the permeability is given by \( \mu = \mu_0 \), and the permittivity,

\[
\bar{\varepsilon}(\omega) = \varepsilon_0 + \sum_{s=1}^{s_{\text{max}}} \frac{\chi_s}{\omega^2 - i\lambda_s \omega + \alpha_s^2}, \tag{8}
\]

where \( s_{\text{max}} \) is the number of oscillators. Here \( \chi_s \) is the coupling, \( \lambda_s \) is the damping and \( \alpha_s \), the natural frequency of the oscillator. Expanding out the dispersion relation \( k^2 - \bar{\varepsilon}(\omega) \bar{\mu}(\omega) \omega^2 = 0 \) leads to a polynomial in \( \omega \) of degree \((2s_{\text{max}} + 2)\). Hence we would generate \((2s_{\text{max}} + 2)\) modes, meaning we need to derive additional boundary conditions, working in the time domain, equation (8) becomes,

\[
D = \varepsilon_0 E + \sum_s P_s, \tag{9}
\]

where each oscillator is driven by the electric field.

\[
E = \bar{P}_s + \lambda_s P_s + \alpha_s P. \tag{10}
\]

Deriving the natural boundary conditions with this procedure is a relatively straightforward,

\[
[P] = 0 \quad \text{and} \quad [\dot{P}] = 0 \tag{11}
\]

Where equations (11) and (7) form the boundary conditions for a temporal material.

4. Simulations

In this section we check the theoretical results by running a simple 1+1D simulation, rather than relying on that traditional doubly spectral analysis (i.e. in both \( \omega \) and \( k \)). In our model the initial conditions are introduced via an auxiliary polarization density \( N \), which couples to the current and immediately decays due to loss. This \( N \) Taking no part in the dynamics except for providing an initial kick to the current, generating the EM wave. Defining \( K \) to be a polarization current offset from the true polarization current \( J \),

\[
\varepsilon \partial_t E = \mu^{-1} \partial_j B - (K + \chi_s \Gamma E), \quad \partial_t B = \partial_j E \tag{12}
\]

\[
\partial_t K = -\Gamma (K + \chi_s \Gamma E) + N, \quad \partial_t N = -\gamma N \tag{13}
\]

where all the fields \( E, B, K \) start with zero amplitude, the parameters are fixed throughout the simulation except for \( \chi_s \) which changes once only at the \( t = 0 \) time boundary. This model enables us to run simulations where the material has a target permittivity changes as a function of time, but where the electromagnetic response of that medium has a realistic dynamics which needs to “catch-up” with any sudden change in properties. On fig. 1 we see the time-domain history of a simulation with cw initial condition and a time boundary at \( t = 0 \) that increases \( \chi_s \) from 0.5 to 1.5. We see the electric and magnetic fields drop at the time boundary, of course this coresponds with a drop in energy, from which we can determine the effective loss each side of the time boundary that is found to be 0.266/ks and 0.0.267/ks. Note the electric field rapidly decays exponential after the time boundary, but is continuous.

5. Conclusions

In this paper we have shown that for a temporal media the usual constant constitutive model is nonphysical. We show that to model EM propagation correctly requires 3 boundary conditions defined by equations (11) and (7). In addition we use numerical simulations to confirm the predictions of the theory presented.

References


4-dimensional covariant helicity states in vacuum and linear media

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Abstract

The notion of helicity in solutions to Maxwell’s vacuum equations in standard 3 + 1 notation is extended to media expressed in 4-D coordinate-free notation. This allows us to significantly generalise the definition of helicity that is associated with the (anti-)self-duality of solutions to Maxwell, a generalization that permits easy extension to media in curved spacetimes.

1. Introduction

Maxwell’s equations support solutions that are invariant under so-called self-duality, a property that is known to have far-reaching implications in areas as diverse as Yang-Mills theory, where the property gives rise to solutions known as instantons, and in General Relativity, where twistor theory has been employed to find self-dual solutions to Einstein’s equations [1]. In Maxwell’s vacuum equations there is a close connection between self-duality and helicity where eigenstates of the Hodge-dual operator are circularly polarized electromagnetic fields. However, so far, to our knowledge, there has not been a close examination of the relationship between helicity and (anti-)self duality beyond vacuum. Here we start to address this.

2. Helicity eigenstates

2.1. Helicity eigenstates of vacuum

The source-free vacuum Maxwell equations are

\[ dF = 0, \quad d \ast F = 0 \] (1)

where the electromagnetic field tensor \( F \), according to an observer with 4-velocity \( u^a \) is given by

\[ F = (u^b \wedge E) + \ast (u^b \wedge B). \] (2)

Equations (1) are invariant under the action of the Hodge dual operation, \( \ast \), i.e. \( F \to \ast F \), since \( \ast^2 F = -F \). The combination

\[ F^\pm = F \mp i \ast F, \] (3)

allows the two vacuum Maxwell equations in Eq. (1) to be effectively combined into a single equation

\[ dF^\pm = 0 \] (4)

for each of \( F^\pm \). The fields \( F^\pm \) are called self-dual and anti-self-dual solutions to Maxwell’s equations because they are eigenstates of the Hodge dual

\[ \ast F^\pm = \pm i F^\pm. \] (5)

When \( \ast \) operates on a general solution \( F \) then

\[ \ast F = \ast(u^b \wedge E) - (u^b \wedge B). \] (6)

The Hodge dual, \( \ast \), structurally makes the interchange

\[ E \to B, \quad B \to -E, \]

implying that an (anti) self-dual field is one that satisfies

\[ E = \pm i B. \] (8)

For massless particles such as photons, these self dual and anti-self dual solutions correspond to states of definite helicity, and we can define the vacuum helicity operator as

\[ b_\ast = -i \ast . \] (9)

The helicity operator has eigenvalues \( \pm 1 \), and the self dual and anti-self dual states correspond to states of positive or negative helicity, i.e. left and right circular polarization. These helicity states are non-interacting propagation eigenstates of the vacuum.

2.2. Helicity eigenstates of dielectric media in curved space-times

The source-free vacuum Maxwell equations can be enhanced by explicitly recognizing the dielectric nature of the vacuum \( \chi = \chi_{\text{vac}} \), which become

\[ dF = 0, \quad d \ast \chi_{\text{vac}} F = 0, \] (10)

while the vacuum (anti)self-dual solutions of Eq. (3) become

\[ F^\pm = F \mp i \ast \chi_{\text{vac}} F. \] (11)

On the other hand, we know that macroscopic electrodynamics in linear dielectric media residing in a curved background space-time is described by generalizing \( \chi_{\text{vac}} \) to some non-vacuum \( \chi \) [2], so that Maxwell’s equations become

\[ dF = 0, \quad d \ast \chi F = 0. \] (12)
In this case, Maxwell’s equations will be invariant to $F \rightarrow \star \chi F$ provided $\star \chi \star \chi F = \pm F$. We postulate that solutions of the form

$$F_{\pm} = A(F) \mp iC(\star \chi F),$$

(13)

are eigenstates of a generalized notion of duality relative to $\star \chi A^{-1}$ within the medium, corresponding to the generalized helicity operator

$$h_{\chi} = -iC \star \chi A^{-1}.$$

(14)

With this generalization, we have allowed $A$ and $C$ to be tensor-valued coefficients. However, in addition to the clear requirement that $A^{-1}$ exists (in other words, that there exists some tensor $A^{-1}$ such that $A^{-1}A = AA^{-1} = \pm C_{\text{vac}})$, the requirement that $F_{\pm}$ satisfy Maxwell’s equation $dF_{\pm} = 0$ places stringent conditions on what $A$ and $C$ could be. One possibility is that $A$ and $C$ are derived from the pullbacks of some chosen diffeomorphisms $\varphi_A$, and $\varphi_C$, such that $F_{\pm}$ can be written

$$F_{\pm} = \varphi_A^*(F) \mp i\varphi_C^*(\star \chi F).$$

(15)

In this case, the commutativity of the exterior derivative with the pullback of a diffeomorphism, $d\varphi^*(\alpha) = \varphi^*(d\alpha)$ for any differential form $\alpha$, guarantees the satisfaction of Maxwell’s equations.

One of the most prominent features of the vacuum duality operator $\star$ is that $\star \star F = -F$, thus we expect some kind of similar condition on $C \star \chi A^{-1}$ to satisfy our expectations for a duality operator. This expectation is also borne out when we examine whether $F_{\pm}$ are eigenstates of $h_{\chi}$. From the generalized helicity operator,

$$h_{\chi} F_{\pm} = -iC \star \chi A^{-1}(AF \mp iC \star \chi F)$$

$$= \pm (-C \star \chi A^{-1}C \star \chi F \mp iC \star \chi F),$$

(16)

which confirms our expectation that $F_{\pm}$ is an eigenstate of $h_{\chi}$ as long as $-C \star \chi A^{-1}C \star \chi F = AF$, or effectively, that

$$-C \star \chi A^{-1}C \star \chi A^{-1} = \chi_{\text{vac}}.$$

(17)

This condition is quite restrictive, and it is unclear whether there exist any tensor-valued $A$ and $C$ coefficients that can satisfy the condition. However, for scalar-valued coefficients $A$ and $C$, Eq. (17) simplifies to

$$\frac{C^2}{A^2} \star \chi \star \chi \chi = \chi_{\text{vac}}$$

(18)

and it is possible to calculate what this corresponds to in terms of the usual 3D parameters $\varepsilon$, $\mu$, etc. Let the 3D constitutive equations read

$$D = \varepsilon \cdot E + \hbar \gamma \cdot H,$$

(19a)

$$B = \mu \cdot H + \varepsilon \gamma \cdot E,$$

(19b)

then the relevant conditions turn out to be [3, 4]

$$\frac{C^2}{A^2} \varepsilon \mu = h, \quad \hbar \gamma = -\varepsilon \gamma,$$

(20)

where $\mu$ is the 3-dimensional inverse of $\mu$ and $h$ is the 3-dimensional identity on the spatial hypersurface orthogonal to $\mu$ [2]. If the medium satisfies the conditions $A^2 \mu = C^2 \varepsilon$ and $\hbar \gamma = -\varepsilon \gamma$, then the states given in Eq. (13) can be interpreted as (anti)self dual solutions with respect to the duality operator $(C/A) \star \chi$, or equivalently as helicity eigenstates with respect to the helicity operator $h_{\chi} = -i(C/A) \star \chi$. In the simplest case of isotropic media characterized by scalar $\varepsilon$ and $\mu$, then the helicity states can be defined as

$$F_{\pm} = F \mp i\sqrt{\frac{\mu}{\varepsilon}} \star \chi F.$$

(21)

For anisotropic media it must be the case that $\mu$ is proportional, but not necessarily equal to $\vareference
Asymmetric frequency conversion with acoustic non-Hermitian space-time varying metamaterial

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Abstract
We experimentally realize an acoustic non-Hermitian space-time varying metamaterial using digital virtualized resonating meta-atoms. By temporally modulating the material gain and loss, we can diminish the main band and achieve high efficiency frequency conversion at the same time due to the gain-loss balance in time domain. We also experimentally demonstrate the asymmetric amplification with such an acoustic metamaterial.

1. Introduction
To extend the capability of metamaterials, many recent developments point to the temporal dimension of metamaterials for wave manipulation [1-3]. Time-varying metamaterials can be used to realize to a much wider range of applications, comparing to the conventional metamaterial approach, including non-reciprocal transmission [4], parametric amplification [5], and frequency multiplexing [6]. It is also proposed that adding the non-Hermiticity into the temporal modulated system, is of great potential to realize the unidirectional amplification [7,8]. Here, based on the digital meta-atoms [9], we can make the constitutive parameters of metamaterials active with gain and also being time-varying. With such a platform, we experimentally demonstrate high-efficiency frequency conversion due to gain-loss balance in time domain and asymmetric amplification.

2. Non-Hermitian space-time varying metamaterial
Here, we start from the experimental realization of the non-Hermitian space-time varying acoustic metamaterial. Figure 1(a) shows the schematic of our platform in which two pairs of speakers ($S_{i=1,2}$) and microphones ($D_{i=1,2}$), termed as digital acoustic meta-atoms (atom1 and atom2), are assembled on a 1D guide. Each pair of speaker and microphone is interconnected by a small microcontroller, which reads the signal from the microphones, and digitally applies a time-domain convolution $y(t)$ and an additional amplitude modulation $a(t)$ applied on the convolution result. The resultant signal is then feedback to the speakers to mimic secondary scatter waves from a metamaterial atom. In this way, the response of the meta-atoms can be modulated in time. In Fig. 1(a), two meta-atoms are separated with a distance $d = 0.04m$ (about $\lambda/8$), and four additional microphones $M_i$ are used for measuring the scattering parameters from the meta-atoms. To temporally control the material gain and loss, a square-wave amplitude modulation $a(t)$ switching between 1 (loss) and −1 (gain) is applied on the two meta-atoms, as shown in Fig. 1(b). In addition, we can control the phase delays of the modulation for two meta-atoms, to realize space-time varying metamaterials. In our implementation, the convolution kernel can be made into a passive Lorentzian in its frequency spectrum ($a$ being 1, as shown in upper panel of Fig. 1(c)) or the “anti-Lorentzian” case for the same convolution kernel but with $a$ being −1 (lower panel of Fig. 1(c)), corresponding to material gain.

Figure 1: (a) Schematic of the time-varying metamaterial platform in a 1D acoustic waveguide. (b) The square-wave amplitude modulation applied on the acoustic metamaterials to achieve alternative material gain and loss, where $T$ and $\xi$ represent the modulation period and dutycycle respectively. (c) Schematic of convolution kernel $y$ with a Lorentzian and anti-Lorentzian line shape,
corresponding to a passive (upper panel) or active atom (lower panel) respectively.

3. Frequency conversion and asymmetric amplification

Next we are going to explore the intriguing phenomena in a time-varying acoustic metamaterial with time modulation. Here, we set modulation frequency \( f_m = 90 \text{Hz} \). The material gain and loss alternate in time, with 0.5 in duty cycle (\( \xi = 0.5 \) in Fig. 1(b)), which results in gain-loss balance in time domain. Figure 2 (a) shows the 2D map of measured reflection amplitude against input and output frequency for a time-varying meta-atom. It can be observed that the amplitude of main band \((m = 0)\) is closed to zero due to the gain-loss balance in time domain. Meanwhile, we can also observe the reflected signals with converted frequency through a relationship \( f_{\text{out}} = f_{\text{in}} + m f_m \) with \( m \) being an odd integer in our case. The sideband components \((m = \pm 1)\) have prominent amplitude peak around the resonance frequency (1kHz). With engineered flexibility, the space-time varying metamaterials can realize the asymmetric amplification through interference. As shown in Fig. 2(b), for output frequency at 1090Hz \((1^{\text{st}} \text{order upconverted Floquet mode at input frequency 1kHz})\), a strong reflection amplitude contrast between forward and backward directions is achieved at \( \Delta \phi = 0.4 \pi \). At \( \Delta \phi = 0.4 \pi \), the up-conversion efficiency of backward reflection (red) can be 130%, almost 7 times larger than that of the forward reflection (black), which demonstrates an asymmetric amplification for our non-Hermitian space-time varying metamaterials together with diminished main band.

![Image](https://via.placeholder.com/150)

Figure 1: (a) The 2D map of measured reflection amplitude against input and output frequency for a time-varying meta-atom. (b) The forward and backward reflection amplitude modulation against the phase delay between two atoms for a space-time varying metamaterial, with fixed output frequency 1090Hz from an input frequency 1kHz. The arrows denote the positions for destructive interference obtained from theoretical calculation.

4. Conclusions

We experimentally demonstrate the efficient frequency conversion and asymmetric amplification for the non-Hermitian space-time varying metamaterials. Such a metamaterial can be used to have optimal control of frequency conversion, and offers new opportunities in studying novel non-Hermitian topological physics in time-varying and nonreciprocal systems.

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References

Novel Topological Photonic Materials
Moiré superlattice induced giant gauge field and Landau levels in bilayer Metacrytals

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Abstract

Moiré super-lattices in two-dimensional Van der Waals (vdW) heterostructures have gained enormous research attention in recent years. In classical physics there has seen a lack in exploring the classical heterostructures. Here we report the first experimental observations of the Landau level flat bands and the associated eigen states in photonics bi-layer Moiré metacrystals. Our work has provided a new route towards engineering of photonic flat bands and could be potentially extended to acoustics and photonic crystal systems.

Introduction

The term Moiré superlattice is used to describe the beating of any two short range periodic patterns and creating a single long range quasi-periodic pattern. Moiré pattern are common occurrence such as two similar slightly intersecting fences, strain measurement, range sensing and image processing. Further above, in the atoms scale moiré pattern are able to greatly modify the electronic properties. Very recently, it was reported that the electronic ground states in the twisted bilayer graphene form a correlated Mott insulator and superconductor, in which the induced flat band might be the gateway towards high temperature superconductor [1,2]. Despite the recent speedy advances, Moiré pattern has been a long-studied topic on, for instance, the effective gauge field for electrons. It has been reported that the Hofstadter spectrum as well as the fractional quantum Hall effect (QHE) states in the bilayer graphene Moiré superlattice [3]. In classical photonics, Moiré patterns are used to create effective gratings to alter the diffractions of light [4]. Plasmonic double layer Moiré pattern is found to emerge as a high circular dichroism optical surface. Very recently, flat bands in double layer photonic crystals are explored for their capabilities in localizing and delocalizing light [5].

In work we report the first emerging effective gauge field and the first observation of the photonic landau levels and its orbitals in Moiré superlattice bilayer metacrytals. Our microwave near field measurements give definite evidence of the flat band, the inter-domain surface states and the momentum-orbital correlations of the Landau levels.

1. The Metacrytals and the Moiré pattern

The bi-layer Moiré metacrytal we study consists of two hexagonal lattice ring metacrystals, each supporting spoof surface plasma. The unit cells for each layer are given in the Fig. 1A-B. Each layer is hexagonally arranged metallic rings holding Dirac cone dispersions at the corners (k and k’ points) of the Brillouin zone due to the C\textsubscript{3v} symmetry. The Dirac points are found at around 12.5 GHz (Fig.1E). Unlike the photonic crystal structures where EM energies mainly reside in the high dielectric inclusions, the spoof plasma structures have the electromagnetic fields tightly confined near to the thin metals. We could take advantage of this property to make two metacrystals strongly interact to each other by closing the distances.

Fig 1: Single and double layer metacrystal with photonic Dirac cone. A. Single layer metacrystal. B. Double layer metacrystal. C. Band diagram of the single layer metacrystal. D. Band diagram of the double layer metacrystal. E. Experimentally measured band diagram of
the double layer metacrystal with Dirac point at 12.648 GHz. F. The flattened Dirac point. G-I. Equi-frequency contour of the Dirac point at 10.6, 12.648 and 14.6 GHz.

Once the two layers are stacked closely, the Dirac cones to each layer, due to the interaction, experience an energy splitting. As is illustrated in (Fig. 1F), the lower energy one is flattened, while the higher energy remains the Dirac cone dispersion similar to the single layer at 12.648 GHz. The lattice constant of the metacrystal is 5 mm, and by introducing an 8% lattice constant difference in the y direction, we obtain a Moiré superlattice whose quasi-periodicity is 108.2 mm.

2. Experimental observations of the photonic Landau levels and the inter-domain surface states.

To observe the Landau levels and the associated orbitals experimentally, we apply the microwave near field scanning system. In the experiments, the excitation and receiving microwave antennas are placed on each side of the metacrystal system. The measurements are taken with the excitation dipole fixed at different locations in y. Due to the lacking of translational symmetry in the y direction in the Moiré pattern, its Fourier components $k_y$ are thus integrated, leaving $k_x$ the only Fourier component.

The band diagram of 0 and 8.66 mm excitation dipole shifts are given in Fig. 2C and 2D respectively. Due to the momentum-orbital correlation, certain excitation dipole position can only excite certain corresponding $k_x$ states. By comoving various measurement results, the full Landau level band diagram can be re-constructed (Fig. 2A). Furthermore, the real space field distributions at 0 mm shift at 11.59 GHz is the conduction channel between the two effective magnetic field domains (Fig. 2E). At 8.66 mm shift and 12.34 GHz, the real space field distribution represents an localized state due to the diminishing group velocity in the $k_x$ direction of the Landau Level.

3. Discussion

The Landau levels in the Moiré-pattern metacrystal are shown to be robust even under very last lattice constant mismatch and thus very small Moiré superlattice quasi periodicity. In our experiments, the Moiré superlattice contains only 22-23 unit-cells in the y directions. The flat band and the conduction channels in the Moiré superlattice may found applications in flat band lasing and reconfigurable wave guiding.

4. Conclusions

We have designed and experimentally observed the Landau Levels and inter-domain conduction channels in the Moiré-pattern metacrystals. The spoof plasma on each layer are shown to be strongly interacting, allowing the metacrystal to show robust Landau levels even under large lattice constant difference. Our designs may be extended other classical wave systems, for instance phononic crystals.

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References

Transport and localization of polaritons in Semi-Dirac honeycomb lattices

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**Abstract**

Strain strongly affects the transport and localisation properties of graphene. For a critical uniaxial compression, graphene shows a semi-Dirac cone with massless and massive dispersions along perpendicular directions. Here we implement strained polariton honeycomb lattices to evidence the highly anisotropic transport of polaritons and to observe directional vacancy states with chiral symmetry. Our work paves the way for the study of transport and localisation in chiral lattices with exotic Dirac dispersions.

1. **Introduction**

Lattices of planar semiconductor micropillars have shown to be an ideal environment to study nonlinear physics and condensed-matter phenomena by the manipulation of exciton-polaritons, quasiparticles with light-matter behaviour [1]. Two great assets of this platform are the ability of engineering lattices with at-will nearest-neighbours hoppings, and the possibility of directly measuring the wave-functions and spectrum associated to the lattice hamiltonian in photoluminescence experiments.

The hamiltonian of the honeycomb lattice has caught great interest because it describes the rich transport and topological properties of graphene. Its experimental implementation in artificial system has allowed the observation of the Lifshitz transition [2] and the formation of a Chern insulator[3]. In this work, taking advantage of the fine control in the engineering of polariton lattices (see FIG. 1(a)), we experimentally investigate the dramatic effect of uniaxial compressions on the transport properties of honeycomb lattices. Such a compression is performed by a constant modification of the inter-micropillar distances along one direction only. It has been proved that for a critical values of the compression, the graphene hamiltonian exhibits a semi-Dirac dispersion [4, 5]: it is relativistic (linear) along the compressed direction and massive (quadratic) along the orthogonal one.

![Figure 1](image_url)

**Figure 1**: (a) SEM image of a photonic graphene made of coupled semiconductor micropillars. The compression is performed along $x$ direction. (b) and (c) measured photoluminescence intensity in momentum space along $k_x$ and $k_y$, respectively, at the edges of the first Brillouin zone (BZ).

2. **Discussion**

We fabricate strained photonic lattices of coupled micropillars from a planar semiconductor microcavity made of 28 (top) and 40 (bottom) pairs of $\lambda/4$ alternating layers of Ga$_{0.05}$Al$_{0.95}$As and Ga$_{0.80}$Al$_{0.20}$As, a $\lambda/2$ cavity spacer of Ga$_{0.05}$Al$_{0.95}$As (with $\lambda = 783$ nm), and twelve GaAs quantum wells embedded at the three central maxima of the electromagnetic field. At 10K, polaritons are created by external excitation of a laser beam, they then decay and photons leak out the cavity encoding their in-plane momentum and energy. By measuring this typical angle-resolved photoluminescence, both in momentum and real space, for unstrained and strained honeycomb lattices, we evidence the semi-Dirac scenario, see FIG.1(b), (c). Furthermore, we probe that polaritons present highly anisotropic transport properties in a semi-Dirac lattice by measuring their propagation length on both direction. We observe extended propagation along the direction in which the semi-Dirac cone has a linear dispersion, and localisation along the direction of quadratic dispersion. Finally, by pumping only one micropillar, on resonant with the Dirac-point energy, we reveal a chiral defect state that arises as a consequence of the driven-dissipative nature of our platform.
3. Conclusions

In this work we give experimental proof of the massless and massive propagation of particles in a semi-Dirac honeycomb lattice and, moreover, we report the observation of a chiral defect state fully directional. The addition of nonlinearity appears as a very promising way to explore nonlinear phenomena (e.g. bistability) in an environment with relativistic and non-relativistic properties.

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References

Hidden symmetry enforced nexus points of nodal lines in layer-stacked dielectric photonic crystals

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Abstract

In an AB-layer-stacked photonic crystal consisting of anisotropic dielectrics, we discover that the unique photonic band connectivity leads to a new kind of symmetry enforced triply degenerate points as the nexuses of two nodal rings and a Kramers-like nodal line. The emergence and intersection of the line nodes are guaranteed by a generalized 1/4-period translation symmetry of Maxwell’s equations. Especially, the bands with a constant $k_z$ and the iso-frequency surfaces nearby the nexus point both disperse as a spin-1 Dirac-like cone, indicating exotic transport features of light at nexus point, such as the spin-1 conical diffraction.

1. Introduction

In photonic crystals (PhCs), the topology of band structures was usually thought of being adequately described by spinless space groups. In this work, we reveals that Maxwell’s equations can possess hidden symmetries which can engender additional symmetry protected band crossings beyond what space group symmetry mandates. We propose a simple layer-stacked photonic structure consisting of anisotropic dielectrics where the hidden symmetry, together with time reversal symmetry, guarantees the emergence of Kramers-like nodal lines (NLS) passing through the Brillouin zone center, and results in unusual photonic band connectivities. Furthermore, we demonstrate that the lowest Kramers-like NL can nearly always intersect with other two nodal rings at two triply degenerate nexus points (NPs), which can be seen as a new kind of magnetic monopoles connecting Berry flux strings in the momentum space. By breaking the hidden symmetry, we lift the two NPs and then achieve type-II and type-III nodal rings in the PhC.

2. Results

The photonic crystal considered here is stacked with two types of anisotropic dielectric layers (A and B) as shown in Fig. 1a. The A and B layers are made up of the same anisotropic material but their principal axes rotate alternatively in the two types of layers. The permittivity tensor in the $xyz$ coordinates is given by

\[
\begin{pmatrix}
\varepsilon_{xx} & 0 & \varepsilon_{xz} \\
0 & \varepsilon_{yy} & 0 \\
\varepsilon_{zx} & 0 & \varepsilon_{zz}
\end{pmatrix}
\]

where $\varepsilon_{xx} = \varepsilon_{yy} = \pm g$ flips its sign between A and B layers, while the diagonal elements are all constant. The band structure of the PhC is plotted in Fig. 1b. The space group of the PhC is $\mathbb{R}^3 \rtimes$Rod(22). The mirror symmetry $M_y$ about $y =$ const. planes and the $PT$ symmetry ensures that $M_y$, even
and odd bands can intersect along nodal lines (red dots in Fig. 1b) on the $k_y = 0$ plane. However, though the space group only supports 1D irreducible representation along the $\Gamma - Z$ line, the band structure shows that two bands with same $\hat{M}_y$-parity always cross along this line regardless of the dielectric’s parameters, and accordingly the two red nodal rings intersect at two NPs (orange dots in Fig.1c). This indicates the PhC system possesses a symmetry beyond the crystallographic space group.

Further analysis shows that the Kramers-like degeneracies along $\Gamma - Z$ is protected by a hidden symmetry of the Maxwell’s equations associated with the fractional period of the components of $\varepsilon$, which can be expressed as a generalized 1/4-period translation along $x$ direction:

$$\hat{T}_z(\xi) = (\hat{P}_x + \hat{S}^{-1} \hat{U} \hat{P}_y) \hat{T}_z(\xi) (\hat{P}_x + \hat{S} \hat{U} \hat{P}_y),$$

(2)

where $\hat{T}_z(\xi)$ denotes the original 1/4-period translation operator, $\hat{P}_x = \frac{1}{2}(\hat{I} \pm \hat{M}_x)$ is the projection operator onto even/odd subsystem, $\hat{U}(x) = \exp\left[\frac{i}{\hbar \varepsilon_0} \int_{0}^{x} \varepsilon(x') d\xi\right]$, and

$$\hat{S} = \hat{I} + (\varepsilon_{\infty}(x) - 1)\hat{c}_z \hat{c}_z + \varepsilon_{\infty}(x)\hat{c}_z \hat{c}_z,$$

transforms the eigenvector from $\Psi = (E, H)^T$ to $\Psi' = (D, \mathcal{E}_x, \mathcal{E}_y, H)^T$. And according to the fact that the photonic bands tend to linear asymptotic dispersion along $\Gamma - Z$ direction, the lowest Kramers-like nodal line will inevitably intersect with the two red nodal rings shown in Fig.1c, forming the NPs. Indeed, the NPs are the terminations of Berry flux strings (NLs), therefore, they can be deemed as a new kind of magnetic monopoles in the momentum space.

The 3D band structure in the vicinity of the NPs shown in Fig.3 exhibit unusual anisotropic dispersion. In particular, both the band structure in the section of $k_z = k_z^{\text{NP}}$ and the iso-frequency surface around the NPs are formed by two conical bands intersecting with a roughly flat band, which resembles the dispersion of a 2D spin-1 Hamiltonian. This property implies that the NPs can be used to realize peculiar effects associated with 2D spin-1 physics. In Fig.2f, we let $\varepsilon_{\infty}^x \neq \varepsilon_{\infty}^y$ to observe the process of hidden symmetry breaking. In this case, the Kramer-like degeneracy along $\Gamma - Z$ is lifted, and the original crossed nodal rings divide into a type-II nodal ring and type-III nodal ring.

3. Conclusions

We discovered that a class of layer-stacked PhCs manifests a hidden symmetry of Maxwell’s equations which directly influences the connectivity of photonic bands and engenders a pair of triply degenerate NPs where three symmetry enforced NLs intersect each other. These photonic NPs not only are worthy of theoretical investigation as a novel kind of magnetic monopoles in momentum space, but they also induce exotic bulk transport effects in the PhC which may lead to prospective applications.

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Topological scattering in Photonic Weyl metamaterial

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Abstract
Weyl points are the sources or drains of Berry flux. Here we experimentally observe the topological signature in the scattering of the photonic Weyl points. Specifically, we discover a helical phase distribution in the angle-resolved reflected waves, representing a winding phase in the momentum space, which leads to an angular momentum beam in the reflection. Our findings pave way for potential device level applications to angular momentum beams with photonic Weyl systems.

Introduction
Controlling the phase profile of light is of the utmost importance in optics. Phase elements such as phase plates contain spatially varying phase profiles that can be imprinted onto an incident wave in transmission or reflection. In particular, phase elements with winding phase profiles for generating vortex beams have received widespread attention because of the broad applications of vortex beams in lithography and optical communications [1]. These phase elements come in various forms, such as liquid-crystal q-plates, spatial light modulators, and metasurfaces [2]. All the above-mentioned devices contain inhomogeneous patterns in the real space, requiring stringent collimation of the incident optical beam to the defect center of the phase profile. Generating the phase profile using translational invariance material in the momentum space (k-space), on the other hand, eradicate the collimation requirement, thus the incident beam could shine on any position of the device with the exact same performance. However, engineering such materials remains challenging and no success has been seen.

Here we demonstrate such a winding phase profile in the momentum space for light do can be gained in the emerging photonic Weyl system. As a key signature of Weyl systems, Fermi arcs that connect between the projections of Weyl points of opposite topological charges have been observed [3]. In phononic, the topological features of the Fermi arcs have been utilized to realize reflection negative refractions [4]. However, the manifestation of the topological nature of Weyl points in their interaction with free space radiations remain obscure in both quantum and classical systems. Scatterings and transport in Weyl semimetals have caught growing attention in both condensed matter and classical physics. In condensed matter systems, the chiral zero modes and the associated magnetoresistance and chiral magnetic effects underlie some highly unusual scattering and transport properties of the Weyl semimetals [5]. It has also been proposed that Weyl semimetals may have handedness dependent Imbert–Fedorov shift within the bulk Weyl material. Electrical conductance is usually measured in the experiments, which has contribution from both the bulk Weyl nodes and the fermi arcs. However, it is generally difficult to perform momentum resolved scattering and transport studies, since the leads that transport the electrons to the Weyl semimetals, by their nature, cannot control the momentum of the input electrons. Therefore, previous attempts to associate the topology to scattering matrix mostly remain theoretical [6-8].

In this work, the vorticial phase profile in the momentum space works for certain elliptically polarized electromagnetic waves reflected by a photonic Weyl system, which represents a key signature of the topological nature of the Weyl points and could leads to collimation-free phase plate for vortex beams generation.

1. Observation of the vorticial phase

Fig. 1 Measurement of the vorticial phase mirror in Weyl metamaterial. (A) The Sketch of the reflection measurement setup in microwave. (B) Analytical, numerical and experimental reflection phases of the Weyl metamaterial and
the associated eigen-polarizations of the Jones matrix for light incident at different azimuth (C) Numerical and Experimental results of the measured 4πt phase winding of the phase mirror. (D) Electric field Amplitude of the incident Gaussian beam. (E) Electric field Amplitude of the vortex beam converted from Gaussian by the vortical mirror by Weyl metamaterial. (F) Phase of the reflected vortex beam. (G) Numerical and Experimental results of the elliptical polarizations of the incident Gaussian beam that can be converted to vortex beam by the Weyl metamaterial.

We found that in the ideal case where the Weyl metamaterial has circular polarization eigenstates and is impedance matched to the vacuum, the scattering matrix around the Weyl point according to $\theta$ can be briefed as:

\[
\hat{S} = e^{-i\theta} \begin{bmatrix} \cos \theta & \sin \theta \\ \sin \theta & -\cos \theta \end{bmatrix}
\]  

This scattering matrix operated on circularly polarized states: $|R\rangle = [i, 1]^T, |L\rangle = [1, i]^T$ gives $\hat{S}|R\rangle = e^{-i2\theta}|L\rangle$ and $\hat{S}|L\rangle = |R\rangle$. Note that the right-handed circular polarization state $|R\rangle$ is converted to the opposite left-handed circular polarization state $|L\rangle$ with an extra $2\theta$ phase, while the conversion from $|L\rangle$ to $|R\rangle$ keeps the phase.

Gaussian beam $|\psi\rangle = \exp\left(-\frac{r^2}{4a^2}\right)|R\rangle$ (Fig. 1D), under $\hat{S}$, is transformed to $|\psi'\rangle = e^{-i2\theta}\exp\left(-\frac{r^2}{4a^2}\right)|L\rangle$, in which $v_r$ is the radial direction Fourier component, $2\sqrt{a}$ is the 1/e position in the momentum space and $1/\sqrt{a}$ is the beam waist in real space. Under cylindrical Fourier transformation, $|\psi'\rangle$ in the real space reads

\[
|\Phi'\rangle = \left\{\int_0^\infty d v_r \cdot v_r \exp(-\frac{r^2}{4a^2}) J_2(v_r r)\right\} \exp(-i2\theta)
\]

Where $J_n$ is the Bessel function of the first kind, $r$ and $\theta$ are the radial and polar angle of the polar coordinate in the real space on the surface of the Weyl metamaterial. The integration in the curly bracket is evaluated numerically and is illustrated in Fig. 1E. The phase profile is a 4πt winding (Fig. 1F) and is consistent with the momentum space phase winding, and the total projected Chern number of Weyl points. The experimental setup to measure the vortical is given in Fig. 1A. The results are illustrated in Fig. 1B.

2. Discussion

Our simulation shows our current metamaterial works under an elliptical polarization shown in Fig. 1G. The maximum differences in the reflected polarizations according to $\theta$ are evaluated according to $\max(|\langle\Phi'(0)|\Phi'(\theta)\rangle||\Psi\rangle - \min(|\langle\Phi'(0)|\Phi'(\theta)\rangle||\Psi\rangle)$, and is within the order of $1e-3$ for the numerical simulations and $1e-2$ for the experiments. Under the elliptical polarizations, the scattering matrix in equation (1) that is valid for circular polarizations can be generalized (supplementary material). The phase profile for both numerical and experimental results shown in Fig. 1C is very close to a linear function, demonstrating its significant potential for a momentum space phase plate. With further optimizing the incidence and introducing higher rotational symmetry than the C2 symmetry in our metamaterial, we can expect even higher performance.

3. Conclusions

We have demonstrated the winding phase of scattering matrix around the projected Weyl points in a photonic Weyl metamaterial. With this novel effect, the photonic Weyl metamaterial is found to be a high-performance collimation-free vortex beam phase plate for certain elliptical polarization. Our work reveals a promising application of the photonic Weyl metamaterials and a rare manifestation of the spiraling structure in the momentum space, which may be applied for unconventional control of wave propagation in photonic systems.

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References


Topological Kagome Lattice Laser

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Abstract

Discovery of new types of photonic topological platforms facilitates the development of novel topological lasers that are potentially immune to cavity defects with high lasing efficiency. We propose a topologically protected laser cavity based on broadband nontrivial edge states in semiconductor photonic crystals with Kagome lattice, and investigate the robustness and dynamics of the lasing cavity.

1. Introduction

Recently, a considerable effort has been made towards the study of non-Hermitian photonic topological insulators (PTIs) by engaging edge states with optical nonlinearity to enable topological lasing. For example, topological insulator laser was experimentally reported in magneto-optical photonic crystals pumped by a static magnetic field to break time-reversal symmetry [1]. Non-magnetic topologically protected edge-mode lasing was proposed and implemented by nontrivial semiconductor ring-resonator arrays, and high efficiency single mode lasing that is robust to cavity defects/disorders was reported [2]. The one-dimensional Su-Schrieffer-Heeger model is another popular approach to generate edge states and topological lasing devices [3].

We demonstrate a new type of all-dielectric photonic topological laser based on semiconductor photonic crystals (PhCs) membrane with Kagome Lattice [4]. The kagome lattice can lift linear degeneracy at K point with structural perturbation and open a broad topological photonic bandgap. We further construct topological cavity with triangular geometry and explore pumping and lasing dynamics of the topological cavities. Our demonstration of lasing from the proposed topological Kagome lattice could provide opportunities for engineering topological edge states for various passive and active photonic integrated devices.

2. Design and Results

The proposed all-dielectric topological structure is based on hole array PhCs on high refractive index InGaAsP membrane, which has Kagome lattice with primitive cell composed of three nanoholes, as schematically depicted in Fig. 1(a). Perturbation to retrieve nontrivial PTIs can be introduced by putting the three nanoholes closer (i.e., shrunken Kagome lattice) or further away (expanded Kagome Lattice) from each other. Unperturbed Kagome lattice has $C_3$ symmetry featuring a Dirac cone at K and K’ points in the momentum space, while the shrunken and expanded Kagome Lattice break the inversion symmetry and reduce the lattice symmetry to $C_3$ symmetry. As a result, the degeneracy at the K (K’) point is lifted and a band gap opens. Since the shrunken and expanded Kagome lattice have distinct valley Chern numbers [5, 6], edge states can be generated at the geometric boundary between them.

![Figure 1: Generation of edge states using PhCs with Kagome lattice. (a) Schematic of the topological waveguide formed by expanded and shrunken Kagome lattice. (b) The corresponding band structure of the topological waveguide, where the black dashed line represents light lines.](image)

We calculate the band structure of the topological waveguide by three-dimensional (3-D) Finite-difference time-domain (FDTD) method (Lumerical software), as shown in Fig. 1(b). We note that edge states with wavelength range of 1468 nm-1578 nm are generated within photonic bandgap of the two perturbed PhCs. Moreover, edge states at wavelengths of 1500 nm-1578 nm are below light line, which guarantees broadband topologically protected light propagation with out-of-plane confinement. The geometrical parameters in the calculation are slab height $h=170$ nm, lattice length $a=500$ nm, and hole diameter $D=150$ nm. The hole-to-center spacing in the primitive cell of the shrunken and expanded Kagome lattice is $d=1.1d_0$ and $d=0.9d_0$, respectively, where $d_0=144$ nm is the hole-to-center spacing of the primitive cell of the unperturbed Kagome lattice. The refractive index of InGaAsP material we use is 3.3.

Based on the perturbed Kagome lattice, we further design a topological triangle cavity that consists of the shrunken Kagome lattice inside of the cavity and the expanded Kagome lattice outside of the cavity, as depicted in Fig. 2(a). To get insight into the optical properties of the cavity, we place dipole sources and monitors randomly around one of the cavity edges to excite and collect resonant modes in FDTD simulations. The cavity supports two types of resonant modes: ring-resonator modes and FP-resonator modes in FDTD simulations. The cavity supports two types of resonant modes: ring-resonator modes and FP-resonator modes in FDTD simulations. For example, when cavity length $L$ is 43.5 μm, nine ring-resonator modes with frequencies of $f_i$ ($i=1, 2, \ldots 9$) and seven FP (Fabry–Pérot)-resonator modes with frequencies of $f_m''$ ($m=1, 2, \ldots 7$) appear, as shown in Fig. 2(b). The ring-
resonator modes arise from the edge modes, which is evidenced by the $E$-field distributions showing that light propagates smoothly along the whole cavity (Figs. 2(c) and 2(d)). In contrast to the ring-resonator modes, the FP-resonator modes experience high reflection from the cavity corners (Figs. 2(e) and 2(f)).

Figure 2: (a) Schematic diagram of the topological triangular cavity, where red and black areas represent the shrunken and expanded Kagome lattice and the white dashed line indicate the boundary between them. (b) Optical spectrum of the cavity when cavity length is 43.5 mm. (c)-(d) Field distribution $|E|$ of the topological ring-resonator modes at frequencies of $f_1=194.8$ THz and $f_2=198.2$ THz, respectively. (e)-(f) Field distribution $|E|$ of the FP-resonator modes at frequencies of $f_2=197.6$ THz and $f_2=199.8$ THz, respectively.

We further study lasing performance of the topological cavity by introducing gain to the InGaAsP material and optically pumping the triangle cavity with a continuous-wave laser at wavelength of 1064 nm from the top of the cavity. We utilize a four-level two-electron model to investigate lasing dynamics of the cavity, where the four-level atomic system is considered as two coupled dipole oscillators $P_a$ (formed by Level 1 and Level 2) and $P_b$ (formed by Level 0 and Level 3) with angular frequency of $\omega_a$ and $\omega_b$, and dephasing rate $\gamma_a$ and $\gamma_b$ [7], respectively. $N_i$ is electron population density probability in Level $i$ and $\tau_i$ ($i,j=0,1,2,3$) is the decay time constant between levels $i$ and $j$. We implement dynamics of electron transition and population intensity modelling by the four-level two-electron model based on 3-D FDTD method. The electron populations of the levels rely on pumping intensity and spontaneous emission decay. We demonstrate that the population inversion of Level 2 relative to Level 1 can be achieved at pump laser intensity of $|E|=3\times10^5$ V/m (Fig. 3(a)). Consequently, lasing at edge state wavelength of $\sim1523$ nm is achieved, as shown in Fig. 3(b). In the simulations, the parameters for the four-level two-electron calculations are $\omega_a=1.26\times10^{15}$ Hz, $\omega_b=1.77\times10^{15}$ Hz, $\gamma_a=1.68\times10^{14}$ Hz, $\gamma_b=1\times10^{12}$ Hz, $\tau_{30}=\tau_{21}=3\times10^{-10}$ s, and $\tau_{32}=\tau_{10}=1\times10^{-13}$ s.

Figure 3: (a) Evolution of electron population density probability with time at level $N_1$ and $N_2$. The inset shows population inversion when the lasing is stabilized. (b) Spectrum of the topological laser.

3. Conclusions

To conclude, we propose an all-dielectric Kagome lattice laser based on InGaAsP membrane platform. We explore the pumping and lasing dynamics of the topological cavities by means of a four-level two-electron model. Our demonstration of lasing from the proposed Kagome lattice scheme could provide opportunities for engineering topological edge states for various passive and active photonic integrated devices and systems.

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References


Topological nanophotonics with time-reversal-invariant plasmonic lattices

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Abstract

In this contribution I will discuss how topological nanophotonics offers a promising path towards the robust control of photons at the nanoscale by exploiting topologically protected boundary modes that are immune to a wide range of defects and imperfections. I will focus on one- and two-dimensional realisations of topological boundary modes in nanophotonics such as arrays of plasmonic nanoparticles.

Currently, the most feasible scheme to realise topological photonics with light confined in nanoscale dimensions and at optical frequencies consists of time-reversal invariant approaches. In particular, crystalline symmetries give rise to topological phases which host protected edge modes [1,2], which are only vaguely reminiscent of the quantum spin Hall effect. The degree at which time-reversal invariant lattices offers topological protection will be discussed. On the other hand, plasmonic lattices offer light modes confined to subwavelength scales, which emerge through the dipole-dipole interactions between all the lattice elements in the array. Dipole-dipole interactions are inherently retarded and radiative, and hence they offer a natural playground for effects such long range interactions and non-Hermiticity, giving rise to rich topological Physics [3]. First, one-dimensional edge modes propagating along two-dimensional lattices will be discussed, showing how, unlike a quantum spin Hall effect, their propagation direction is determined by the position of the source within the unit cell through the inhomogeneous spin angular momentum of the electromagnetic field [5]. Next, zero-dimensional modes localized at the corners of a two-dimensional lattice will be considered and the protection of these higher order topological modes will be analysed in detail [6].

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References

**Nodal link in double diamond photonic crystal**

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**Abstract**

We demonstrate nodal links in momentum space using a dielectric double diamond structure. We also characterize the topological natures of the nodal links. These topological natures are summarized into non-Abelian charges.

1. **Introduction**

Topological physics deals with degeneracies generated in momentum space. A set of degeneracies in 1D-shaped straight or curved line are called as a nodal line. Nodal lines are classified as a nodal ring, a nodal link, a nodal ring, or a nodal knot [1]. The nodal link consists of two or more rings linked without mutual intersection. To describe the topological nature of the nodal line, a recent study has been proposed non-Abelian band topology where the topological charges of the nodal lines are expressed as quaternion [2].

There are many studies on the nodal lines by using metals [3], semimetals [4] or electrical circuits [5]. A few studies also show the nodal lines in photonic systems [6]. However, there is no study that realizes the nodal link by using dielectric medium. Furthermore, most of previous works have not fully discussed the topological nature in relation to numerically calculated topological charges.

Here, we demonstrate the nodal links using dielectric double diamond structure. The non-Abelian topological charges are also calculated.

2. **Dielectric double diamond structure**

Our double diamond structure consists of two single diamonds. The surface of one single diamond is given by

\[
f(x) = \sin(x_1 + x_2 + x_3) + \sum_{i=1}^{3} A_i \sin(x_1 + x_2 + x_3 - 2x_i),
\]

where \( X = (2\pi/a)(x - xa/2) \) is normalized local coordinates defined with the lattice constant \( a \), global coordinates \( x \), the summation of the lattice vectors \( a = a_1 + a_2 + a_3 \), and the coefficient \( \gamma \) which concerns with displacement of the diamond. All the coefficients \( A_i \) are different from each other and they are not equal to one. Because sets of \( x \) such that \( f(x) = f_c \) makes the total geometry double diamond structure as shown in Fig. 1a.

To get the nodal link, an eigenfrequency problem derived by the Maxwell equation is solved for all \( k \)-points of the Brillouin zone in 3D momentum space. These band structure calculations are carried out by the MIT Photonic-Bands (MPB) package. Sets of the degeneracies by the 3rd and 4th bands (orange ring) and 4th and 5th bands (cyan ring) form the nodal link as shown in Fig. 1b. Because of the periodicity of the first Brillouin zone, this link is infinitely repeated along the connection direction.

3. **Non-Abelian topological charges**

Topological states of the nodal link can be described as follows. First, we assign new band numbers \( n = 1, 2, 3 \) to 3rd, 4th, and 5th bands, respectively. Next, we consider a closed loop encircling a point on the orange ring by the 3rd \((n=1)\) and 4th \((n=2)\) bands. Along the loop, the following correlation vectors are calculated:

\[
[C_n(k)]_m = (u_{k_0}^m | u_{k}^n) = \int_{cell} (u_{k_0}^m)^* \cdot u_{k}^n d^3x
\]

The sets of the correlations exhibit \( \pi \)-rotations of the Bloch states of the 3rd and 4th bands while the sets of the 5th band do not show (Fig. 2a). If the Pauli matrices are expressed as \( \sigma_1, \sigma_2, \) and \( \sigma_3 \), the topological charge for this closed loop is \( -i\sigma_3 \). Applying similar analysis to the closed loop enclosing the cyan ring (by the 4th and 5th bands) gives the topological charge \( -i\sigma_1 \) (Fig. 2b). By the relation \( -i\sigma_2 = (i\sigma_3)(-i\sigma_1) \), the topological charge \( -i\sigma_2 \) is obtained from the loop which encloses both orange and cyan rings (see Fig. 2c).

All these \( -i\sigma_1, -i\sigma_2 \) and \( -i\sigma_3 \) can be replaced as quaternions \( i, j, \) and \( k \). Therefore, a closed loop which encloses the ring(s) of the nodal links are classified under the quaternion groups. And, because of anticommuting properties of these quantities, we can conclude that they are non-Abelian.

4. **Conclusions**

We have shown that infinitely connected nodal link can be formed in a dielectric double diamond structure. The dielectric photonic crystal and theoretical approaches

\[
\sum_{i}(x_i - x_{i+1})
\]

constitute a 3D diamond structure. Adding a structure defined by \( f(x) > f_c \) makes the total geometry double diamond structure as shown in Fig. 1a.
proposed in this study will allow for experimental observation of searching nodal-link photonic crystal.

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References

Figure 1: Double diamond photonic crystal and its nodal links. (a) Real space geometry with \( A = [1.19, 1.37, 1.28], \( \gamma = 0.08, \) and \( f_c = 2.0. \) Dielectric permittivity is 16.0 for both structures. The face-centered cubic primitive cell is defined by \( a_1 = a/2[0, 1, 1], a_2 = a/2[1, 0, 1], \) and \( a_3 = a/2[1, 0, 0]. \) (b) Nodal links in 3D momentum space.

Figure 2: Correlation sets of the closed loops that enclose (a) the orange, (b) the cyan and (c) both two rings.
Topological photonics: Mistaken paradigms and new opportunities

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Topological states of matter were first discovered in the field of solid-state physics but recent contributions are proving their existence in diverse fields of science. To mention a few, topological surface states have been recently identified in the fields of optics [1], acoustics [2] and in excitonic and polaritonic materials [3].

Most of these cross-disciplinary designs have been directly inherited from concepts previously discovered in electronic materials. Nevertheless, these different physical mechanisms, should lead to distinct effects with interesting properties of their own. Unfortunately, those assets will remain hindered if the research on topological effects in these fields continues to be exclusively based on analogies with solid-state systems.

In this work, through the application of the recently developed method of “Topological Quantum Chemistry” [4] (TQC) to photonic crystals and the numerical calculation of Wilson loops and different topological invariants [5], surprisingly, we discovered that certain paradigms in the design of Photonic Topological insulators are not strictly truthful. Moreover, the versatility of these methods allowed us to design novel topological photonic systems with unprecedented physical properties.

In particular, we will introduce the first instance of fragile topology in a physical system [6]. Moreover, we will show how one of the paradigmatic designs in Topological Photonics, assumed to present Z2 topological response, is actually a higher order photonic TI sustaining topologically protected corner states [7,8]. Finally, we will introduce our latest advances in the design of 3D photonic crystals with topological features such as Weyl points, section Chern numbers, and novel emerging properties.

References:
Three-dimensional metamaterials and two-dimensional photonic crystals for topological photonic phase

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Abstract
My recent work on 3D topological semimetals based on metamaterials and 2D topological insulators based on photonic crystals will be presented in this talk. In the first part, topological semimetals whose topological phases arising from effective optical properties, hyperbolicity and chirality, will be covered. In the latter part, exploration of 2D nontrivial topology characterized by quantum Hall phase and Zak phase will be presented.

1. Introduction
Conventional photonics has been studied actively in terms of photonic crystals and metamaterials, whose optical responses mainly originate from the periodic arrangement and homogenized effective properties, respectively [1]. The introduction of topological characteristics to photonic crystals and metamaterials has opened a new field called topological photonics. Topological photonic crystals and metamaterials have shown unprecedented optical features, whose nontrivial topology originates from the crystalline structures and effective optical properties. In this talk, my recent work on 3D topological metamaterials and 2D topological photonic crystals will be covered.

2. Results and discussion
2.1. Metamaterials-based approach towards topological semimetals
The defining property of the topological semimetal phase is a degeneracy between topologically distinct photonic bands called Weyl degeneracy. I present a 3D topological metamaterial that has extremely broadband topological surface states. Because of the effective chiral and hyperbolic features [2] in the long-wavelength limit, the metamaterial has a Weyl point at zero frequency and its Weyl partner at finite frequency [3]. Whereas previously reported topological surface states have limited bandwidth that has both lower and upper frequency limits, we demonstrate the extremely broad topological surface states that have no lower limit.

2.2. 2D topology studied by coupled dipole method
Artificial crystalline structures that are arranged periodically in 2D give rise to the 2D topological phase. The 2D topological phases can be theoretically modeled by the coupled dipole method [5]. It provides a full analytic description of the 2D periodic system by assuming particles as point dipoles and corresponds to a direct analogy of tight-binding approximation. Firstly, the polarization-dependent topological features of a 2D Su-Schrieffer-Heeger (SSH) model are shown [6]. As opposed to previous studies in which only transverse magnetic modes are considered, independent control of topological features by exploiting polarization as an additional degree of freedom is presented. Conventional and higher-order topology manifested by the topological edge and corner modes is studied under an open boundary condition by exploiting the polarization dependency. Lastly, theoretical modeling of the quantum Hall phase in a gyrotropic photonic crystal is covered [7]. Previously, topological features of such photonic crystals have been investigated analogously by mapping the photonic states to the electronic wavefunction. However, this work provides a purely optical framework for modeling the quantum Hall phase in photonics.

3. Conclusions
Recent work on 3D topological metamaterials and 2D topological photonic crystals is presented. My recent on-
going work on developing a python-based open software based on the coupled dipole model will be also included.

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References


Topological Singular Points in Photonic Crystals with Broken Symmetry

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Abstract
We demonstrate that it is possible to deterministically generate topologically-protected bound states in the continuum (BIC) by breaking $C_6$ symmetry of triangular-lattice photonic crystals. Furthermore, we found a variety of pair-creation and annihilation processes of circularly-polarized states, which are another type of singular points, by symmetry breaking. We also clarify that there is an intriguing conservation rule of two different topological charges, which account for vectorial nature of these singularities.

1. Introduction
Various intriguing phenomena associated with nontrivial topology of reciprocal-space Bloch wavefunctions are extensively studied in photonic periodic systems [1,2]. It is extended even to non-Hermitian periodic systems [3], and it was shown that non-trivial topology can be created by non-Hermitian perturbation for photonic periodic systems, namely, gain and loss [4]. Yet another topological nature of photonic periodic systems related to far-field polarization vectors is currently gathering attention [5-7]. These polarization vectors are reciprocal-space Bloch wavefunctions and intriguing topological properties of singular points arise from topological charges determined from them. A bound state in the continuum (BIC) is one of singular points of polarization vectors in the reciprocal space, which has an infinite quality factor although it is positioned within the radiation continuum [5]. Although it had been known for years in a sense that an optical BIC can exist at the $\Gamma$ point of photonic crystals, protected by the crystal symmetry, counter-intuitive off-$\Gamma$ BICs were recently found in a certain types of photonic crystals. It was also clarified that these off-$\Gamma$ BICs are topologically protected and posses various interesting topological properties [6,7]. However, these off-$\Gamma$ BICs are accidentally formed, and there is no systematic and deterministic way to form off-$\Gamma$ BICs.

In this talk, we demonstrate that it is indeed possible to form off-$\Gamma$ BICs deterministically by breaking $C_6$ symmetry of triangular-lattice photonic crystals. We also demonstrate a variety of pair-creation and annihilation processes of circularly-polarized states, which are another type of singular points, by symmetry breaking. We will show that all these processes can be explained by conservativo of two types of topological charges.

2. Generation of off-$\Gamma$ BIC by symmetry breaking
We start from a simple triangular-lattice air-hole photonic crystal slab structure, shown in Fig. 1(a,b). There is a symmetry-protected BIC at the $\Gamma$ point of the lowest TE-band in Fig. 1(c). We note this at-$\Gamma$ BIC because it is a higher-order BIC having a topological charge greater than unity. To analyze the topological charge, we plot Fig. 1(d) which shows a line plot of polarization vectors for radiation from the photonic crystal. The direction of lines corresponds to the direction of the long axis of the polarization ellipse, and one can see that the direction of this vector winds twice around this at-$\Gamma$ BIC point, meaning that the topological charge is -2. This at-$\Gamma$ BIC is protected by $C_6$ symmetry.

It is known that the existence of BIC generally requires $C_2$ symmetry at least, but if the crystal possesses $C_2$ symmetry only, the topological charge cannot be greater than unity. Hence, we can anticipate that when we continuously change the crystal symmetry from $C_6$ to $C_2$, at-$\Gamma$ BIC may split into a pair of off-$\Gamma$ BIC having a topological charge of -1. Since this is just a speculation from the conservation of the topological charge, next we examine this possibility by a concrete example.

To reduce the crystal symmetry from $C_6$ to $C_2$, we introduce uniaxial deformation of the crystal shown in Fig. 1(e). In this example, we change the angle between two translational unit-vectors from 60° to 58°, meaning that the crystal is compressed in the x axis by 3%. As a result, the crystal symmetry becomes $C_2$. Numerical simulations show that there are a pair of ultrahigh-$Q$ states appeared on the $k_x$ axis (Fig. 1(f)). By varying the deformation parameters, we confirmed that these paired states split from the single at-$\Gamma$
BIC and move along the $k_x$ axis. Figure 1(g) shows a line plot of polarization vectors for radiation from the photonic crystal, which tells us that each high-$Q$ state has a topological charge of -1. We also confirmed that nodal lines of $x$- and $y$-components of the polarization vectors intersect at the high-$Q$ points, proving that these two points are strictly BIC having infinite $Q$.

This result directly demonstrates that one can generate off-$\Gamma$ BICs by simple symmetry breaking. The existence of higher-order at-$\Gamma$ BICs is guaranteed by the crystal symmetry, and any infinitesimally-small perturbation reducing the symmetry from $C_6$ to $C_3$, produces off-$\Gamma$ BICs. Hence, this method enables deterministic generation of off-$\Gamma$ BICs, which is the most remarkable difference from previous off-$\Gamma$ BICs [8].

3. Generation and annihilation of circularly-polarized states by symmetry breaking

Next, we introduce another type of symmetry breaking to the same simple triangular-lattice air-hole photonic crystals. Here, we reduce the crystal symmetry from $C_6$ to $C_3$ by breaking the inversion symmetry. We found that starting from the higher-order symmetry-protected at-$\Gamma$ BIC with a topological charge of -2, a variety of creation and annihilation processes of circularly-polarized states, which are another type of topological polarization singular points.

Furthermore, in the talk, we will discuss what governs the whole processes including generation of off-$\Gamma$ BICs and circularly-polarized states, and clarify that there is an intriguing conservation rule of two different topological charges, which account for vectorial nature of these singularities.

4. Further studies

Recently, we have fabricated the proposed structures and have successfully observed these topological singular points created by symmetry breaking. In the conference talk, we will present the recent results of the experimental study.

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References

Metamaterial enabled new devices and applications
Programmable absorbing metasurface for active scattering manipulation

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Abstract

We present a programmable absorbing metasurface for active scattering manipulation. A metasurface unit with switchable perfect absorption and perfect reflection is achieved by incorporating a PIN diode into a typical metamaterial absorber, where the absorption and reflection functions can be switched by biased voltages. The simulated field results shows that the scattering properties can be controlled by changing the voltage distribution on PIN diodes on the metasurface.

1. Introduction

Absorbing metasurface, as a kind of subwavelength planar artificial structures, have attracted much attention in recent years [1]. Compared with the passive absorbing metasurface, utilizing active components such as PIN diodes [2] or varactors [3] to achieve electrically switchable metamaterials is an efficient approach.

In this paper, we present a programmable absorbing metasurface working at 4.5 GHz. The proposed unit cell can achieve good absorption/reflection via switching of a PIN diode. The manipulation of the scattering electromagnetic waves are achieved by the absorbing metasurface with different state distributions of PIN diodes.

2. Unit cell

The structures and detailed dimensions of the unit cell of the proposed programmable absorbing metasurface are shown in Fig. 1. The dielectric material is Rogers RT5880, which has a relative permittivity of \( \varepsilon_r = 2.2 \) and dielectric loss of \( \tan \delta = 0.0009 \). The thickness of the dielectric layer is \( h = 1.575 \) mm and the period constant is \( p = 10 \) mm.

The unit cell introduces the switchable resonator method to control the reflection/absorption of the incoming waves, and the microstrip patch is associated with a PIN diode for status switching of the incident electromagnetic wave. A bias line is employed to provide direct-current (DC) bias at the zero-electric-field point of the non-radiation metal patch edge. Besides, we introduced an open-ended radial stub to isolate the radio frequency (RF) signal and minimize the reflection loss.

The PIN diodes HSMP-3862 from Avago are employed as RF switches. A parallel lumped elements are applied to describe the two status of the PIN diode, whose parameters are \( R_{\text{on}} = 3 \) Ohm and \( C_{\text{on}} = 0.15 \) pF for forward bias (denoted as ON state), while \( R_{\text{off}} = 6000 \) Ohm for reversed bias (denoted as OFF state), respectively.

Figure 2 gives the simulated reflection coefficients and absorption of the unit cell. Since the central plane is a continuous copper film with small via holes, its transmission \( S_{21} \approx 0 \), and thus the absorption can be approximated as \( A \approx 1 - |S_{11}|^2 \).

At the working frequency 4.5 GHz, the normalized reflection coefficients with ON/OFF-state of PIN diode are 0.005 and 0.995, respectively, for \( y \)-polarized incidence. This means that the incident power has been largely absorbed or reflected by the metasurface under the two switchable status of PIN diode.

3. Programmable absorbing metasurface

A programmable metasurface is designed for active scattering manipulation via changing the voltage distribution on the PIN diodes. The designed metasurface includes \( 40 \times 40 \) unit cells. For instance, the reconfigurable metasurface is applied with coding sequences to mimic as a square (Pat-
Figure 2: Reflection coefficients with ON/OFF-state and absorption with ON state.

Figure 3: Illustration of the design of the programmable absorbing metasurface encoded with (a) Pattern 1 and (b) Pattern 2.

Figure 4: Normalized electric field distribution at the plane 8 mm above the programmable absorbing metasurface encoded with (a) Pattern 1 and (b) Pattern 2.

original pattern. Fig. 5 gives the comparison of simulated far-field directivity curves of the metasurface and an equivalent metal plate. The curves shown nearly same trend, demonstrating the validity of the programmable absorbing metasurface for active scattering manipulation.

4. Conclusions

We have proposed a programmable absorbing metasurface working at 4.5 GHz for active scattering manipulation. The switchable nearly perfect absorption/reflection of the unit cell was achieved by introducing a PIN diode in a typical absorbing metasurface unit. The scattering control feature of the programmable metasurface was demonstrated via applying different coding sequences of ON/OFF status of PIN diodes. Numerical simulation confirms the functionality of the proposed metasurfaces. The proposed programmable absorbing metasurface can be used in electromagnetic circumstances, including RCS reduction, electromagnetic camouflage.

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Planar Vortex Beam Generator for Circularly Polarized Incidence Based on FSS

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Abstract—In this paper, a new technique to design a low-profile planar vortex beam generator is proposed based on microwave frequency selective surface (FSS). Each unit cell, behaving as a spatial phase shifter, is composed of a stack of patches and grids separated by thin dielectric substrates. A simple equivalent circuit model, composed of transmission lines coupled together with shunt capacitors and inductors, is presented to analyze this structure. The prototype of the proposed planar OAM generator operating in X-band is designed, fabricated and experimentally characterized.

Index Terms—orbital angular momentum, frequency selective surfaces, low-profile.

I. Introduction

Electromagnetic waves can carry both spin angular momentum (SAM) and orbital angular momentum (OAM) during propagation. For SAM, there exist only two states since it is related with the polarization state of the beam. On the other hand, beams carrying OAM are characterized by a helical phase of $e^{i\phi}$ with a phase singularity on the beam axis, where $\phi$ is the azimuthal angle and $l$ is an arbitrary integer indicating the topological charge of OAM mode [1]. Hence, OAM states can theoretically take any integer value. Due to the orthogonality between different OAM modes, OAM mode division multiplexing is considered as a promising transmission technique.

In this paper, an OAM generator is investigated through the design of frequency selective surfaces (FSS). A third-order bandpass FSS is proposed to operate under circularly-polarized illumination, which mainly relies on the coupling between the metallic layers. An equivalent circuit model for such FSS design is also exploited to analyze the operating principle. An ultra-thin OAM generating device is designed for X-band operation with a thickness of only 0.067λo. The experimental results validate the generation of highly efficient vortex beam carrying OAM mode in the passband.

II. Principles and Results

Fig. 1 shows the three-dimensional (3D) view of an elementary cell of the proposed FSS design. The structure is initially built from a capacitively coupled miniaturized-element frequency selective surface (MEFSS), which uses a circular grid with a rectangular patch loaded in the circular gaps. A comprehensive analytical design and synthesis procedure for the MEFSS is reported in [2]. Using this method, a second-order bandpass response MEFSS is firstly designed. Then, in order to introduce PB phase by rotating the unit cell, a circular grid is used instead of the wire grid. Rectangular patches are designed to generate two different frequency responses for vertical (y-axis) and horizontal (x-axis) components of the incident circularly polarized wave. However, within a second-order bandpass MEFSS, the maximum coverage of the transmission phase is less than $\pi$. The MEFSS unit usually acts as a spatial phase shifter, providing an increase in phase shift variation as the increase of response order. Therefore, a rectangular patch is embedded in the center of the circular gaps to add another order for the equivalent filter circuit. Due to the strong coupling of the gap between rectangular patch and the arc grid in vertical direction, the unit cell presents an extra resonance compared to the other direction.

For better understanding the operation principle of the structure, a generalized equivalent circuit model is proposed. The elements of the equivalent circuit model are the same for both orthogonal polarizations, as shown in Fig. 2(a). The rectangular patches are regarded as capacitors $C_{x1}$, $C_{x2}$, $C_{y3}$ for x-direction and $C_{y1}$, $C_{y2}$, $C_{y3}$ for y-direction, while the circular grid is regarded as inductors $L_x$ and $L_y$. Since the rectangular patch is embedded in the circular gap, the equivalent capacitor is parallel with the inductor of the grid. The thin dielectric substrates separating each metallic layers are equivalent to short transmission lines (STLs) which can be taken into account in the model by a series inductor $L_{Ti}$.
The half spaces on the two sides of unit cell structure can be represented by free space characteristic impedances $Z_0 = 377 \, \Omega$. As it can be observed, the circuit model is a third-order bandpass filter as shown in Fig. 2(b). Two of the resonators are composed of the capacitors $C_{12}, C_{23}$ and inductors $L_{13}, L_{23}$, respectively. The parallel capacitor $C_{01}$ and inductor $L_s$ together comprise the middle layer resonator.

Then the performance of the unit cell under circularly polarized incidence is considered. The incident wave is set to a left-hand circularly polarized (LHCP) wave. Fig. 3(a) shows the transmission coefficient of the cross-polarized wave when the unit cell is rotated around z-axis by step of $\pi/12$. The unit is able to convert a left-hand circularly polarized wave to the cross-polarization (right-hand circularly polarization, RHCP) where the amplitude of the cross-polarized transmission coefficient is close to 1 at 10.7 GHz and above 0.8 between 10.2 GHz and 11.2 GHz. Moreover, as illustrated in Fig. 3(b), the transmission phase has the same phase gradient of $\pi/6$, which is approximately two times the rotation angle. The unit cell has nearly 100% conversion efficiency at 10.7 GHz. Here the conversion efficiency is defined as the ratio of the energy carried by the cross-polarized component to the total transmitted energy.

Fig. 4. Measured phase and amplitude distributions of cross-polarized component in transmitted wave at 10 GHz, 10.7 GHz and 11.1 GHz, respectively. (a)-(c) Phase distribution in xoy plane for $z = 100 \, \text{mm}$.

III. Conclusion

In summary, a new method to generate highly efficient vortex beam carrying OAM mode in X-band is proposed based on the use of frequency selective surfaces. The proposed elementary cell structure has the ability to convert the circularly polarized incident wave into its cross-polarized component with nearly 100% conversion efficiency. A compact planar OAM generator is designed and fabricated based on the proposed unit cells. The measurements demonstrate that a cross-polarized transmitted component carrying OAM mode of $l = \pm 2$ can be generated with high efficiency. The proposed method provides a robust and efficient method to generate OAM modes at microwave frequencies.

References


Metamirror for generation and control of Airy beams

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Abstract

Due to their intriguing diffraction-free, self-bending, and self-healing properties, Airy beams have attracted enormous research interests. An electronically reconfigurable metamirror is proposed to generate Airy beams on a wide frequency range by designing two distinct coding states with opposite reflective phase of 0° and 180° as digital bits of “0” and “1” states. Both numerical simulations and experimental measurements are performed to verify the Airy beam properties from 9 GHz to 12 GHz.

1. Introduction

Electromagnetic (EM) wave control has become possible today thanks to metamaterials. Moreover, in recent years a planar version of metamaterials referred to as metasurfaces has been developed. These new structures present the main advantage of having reduced profile and therefore reduced losses \cite{1}. By controlling the reflection and/or transmission characteristics of metasurfaces, they have been successfully implemented for anomalous reflection and refraction \cite{2-3}, polarization control \cite{4}, vortex beams generation \cite{5}, imaging holograms \cite{6}, lenses \cite{7}, and so on.

In this study, we propose to use an electronically engineered metamirror to synthesize a reconfigurable Airy beam by modulating a plane wave imposed by a predesigned coding phase profile. The non-diffraction and self-bending properties of the Airy beam are analyzed in simulations and validated by measurements at microwave frequencies. Frequency agility and deflection angle control of the Airy beam are particularly highlighted in this work.

2. Airy beam function

The electric field envelope of a finite energy 1D Airy beam can be described as \cite{8}:

\[ \phi(x, \xi) = A i \left[ b x - \left( \frac{\xi}{2} \right)^2 + i a \xi \right] \exp \left[ a x - \frac{a \xi^2}{2} \right] - i \left( \frac{\xi^3}{12} + i \frac{a^2 \xi}{2} + i \frac{a \xi^2}{2} \right) \]

where \( A i = \frac{1}{\pi} R \int_0^\infty \cos(t^3 + xt) \, dt \) is the Airy function. The decay factor \( a \) is a positive value to ensure containment of the infinite Airy tail. The initial field envelope of Airy beam is given by:

\[ \phi(x, \xi = 0) = A i(bx) \exp(ax) \] (2)

In order to generate Airy beam, the phase profile as a function of \( y \)-coordinate along the unit cell array is defined as:

\[ \varphi = \arg(\phi(x, \xi = 0)) - \frac{\pi}{2} \] (3)

3. Implementation of Airy beam in a metamirror

The electronically engineered metamirror is shown in Fig. 1. The dielectric substrate used is ARLON AD450 with relative permittivity \( \varepsilon_r = 4.5 \) (\( \tan \delta = 0.003 \)) and thickness \( t = 1.52 \) mm. The elementary cell of periodicity \( p = 6 \) mm is composed of two strips with width \( w = 0.5 \) mm separated by a gap \( g = 1.9 \) mm and backed by a continuous ground plane. An Aeroflex MGV 125-08 varactor diode presenting a dynamic capacitance varying from 0.055 pF to 0.6 pF is inserted in the unit cell for reconfigurability mechanism.

In order to verify the validity the aforementioned Airy beam design, numerical simulations are firstly performed. The phase distribution alternating between \( -\frac{\pi}{2} \) and \( +\frac{\pi}{2} \) is applied to the metamirror along the \( x \)-axis. The metasurface is then illuminated by a plane wave in simulations.

In the experiments, the metamirror is illuminated by a quasi-plane wave illumination emitted from a horn antenna placed at a distance of more than 100 cm. Electric near-field obtained from both simulations and measurements are presented in Fig. 2(a). It is worth noting that the Airy beam generator based on the reconfigurable metamirror operates over a broad frequency range spanning from 9 GHz to 12 GHz. Moreover, the radiation direction of the Airy beam can be controlled in steering by introducing an additional phase profile, as illustrated at 10 GHz in Fig. 2(b). It can be observed that the Airy beam is deflected according to the respective additional phase applied.
4. Conclusions

Generation of Airy beam has been demonstrated from 9 GHz to 12 GHz using an electronically engineered metamirror. The radiation direction of the Airy beam can further be controlled by adding an additional phase gradient to the phase profile of the Airy function.

References


Superscattering and directive emission via mode stacking in subwavelength core-shell meta-atoms

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Abstract
Designing a subwavelength structure with multiple degenerate resonances at the same frequency can vastly enhance its interaction with electromagnetic radiation, as well as defining its directivity. In this work we demonstrate that such ‘mode stacking’ can be readily achieved through the careful structuring of a high-permittivity spherical shell, with either a metallic, or a low permittivity dielectric (air) core. We examine the behaviour of these structures both as scatterers of plane wave radiation and as directive antennas. In the case where the core is metallic this leads to a superposition of the magnetic and electric dipoles, causing suppression of backscattering and unidirectional antenna emission. For an air core, the electric dipole and magnetic quadrupole are superimposed, the backscattered power is maximized and antenna emission is bidirectional. This is shown experimentally at microwave frequencies by observing the radar cross section of core-shell spheres and we propose two antenna designs demonstrating different emission patterns defined by the superposition of multiple modes.

1. Introduction
The resonant modes of a subwavelength structure define its interaction with electromagnetic radiation, and are fundamental to the operation of many types of antennas, sensors, and metamaterials. Any given resonance will have an associated charge, current or displacement current in a given structure, which corresponds to a specific farfield radiation pattern. In many conventional structures, the fundamental natural resonances are separated in frequency and do not spectrally overlap significantly. In recent years however there has been a growing interest in the use of tailored systems where two or more resonant modes can be ‘stacked’ - made to share a resonant frequency, leading to enhanced interaction with electromagnetic radiation and improved directivity in the farfield[1–8].

This ‘mode stacking’ has enabled significant progress in controlling the power and directionality of radiation scattered by resonant particles when illuminated by a plane wave, which is key for technologies from light trapping in solar cells[9], [10] to radar detection[11]. The spectral overlap of two or more modes in a variety of geometries has produced powerful scattering, that surpasses the theoretical single channel limit[12] in both the microwave[1–3] and optical regimes[13], [14] as well as producing directional emission and suppressed backscatter. The opposite case, where backscattered power is maximized has also been posited theoretically[15],[16] and recently experimentally verified by the authors[17].

Figure 1: Illustrating the concept of ‘mode-stacking’ where two or more modes are superimposed spectrally and their far field patterns interfere to control the directivity of scattering (or radiation) from a dielectric sphere[17]. (a) An illustration of the combination of electric and magnetic dipoles (ED+MD, first Kerker condition), leading to constructive interference in the forward direction and destructive in the reverse. (b) shows the combination of the electric dipole and magnetic quadrupole (ED+MQ) where the emission is bidirectional and scattered power in the reverse direction is maximized (a ‘superbackscattering’ condition[15]). (c) Shows Comsol simulations of the normalised electric near-fields of these three modes. The field distributions provide clues as to how these modes can be tuned separately to achieve an overlap condition.
A second key area where mode stacking is producing important results is the field of dielectric resonator antennas (DRAs). High-permittivity ceramics have been structured to overlap pairs of modes and produce unilateral emission[18], [19] as well as multiple modes simultaneously to produce highly directional emission[20], [21], and water-based antennas have also shown the capacity to act as an easily fabricable Huygens source[22]. In all cases however the choice of mode combinations is somewhat limited and does not reflect the variety of emission patterns that can be achieved by structuring the resonator in order to overlap different choices of modes.

In this study we show the versatility of a simple, high symmetry geometry - a two layer (core-shell) sphere for utilizing mode stacking to control microwave emission when resonances are driven either by a plane wave or by an antenna feed. We draw parallels between the two cases to demonstrate the applicability of the physics to a variety of fields. In terms of scattering, we show how the radius of different core-shells structures can cause different combinations of modes to overlap spectrally, either suppressing or enhancing the backward scatter. We experimentally demonstrate this using a metallic core to combine the electric and magnetic dipoles in order to reduce backward scatter, and an air core to combine the electric dipole and magnetic quadrupole to enhance it. Finally, we show that these same geometries can also be used to create unidirectional and bidirectional dielectric resonator antennas and we propose two designs to demonstrate this.

2. Discussion

The principle of mode stacking is laid out in Figure 1. Through examining the far-field radiation pattern for each fundamental (Mie) resonance of a dielectric sphere, it can be seen that forward and reverse scattered light will possess a different phase depending on the scattering mode. When the far field contributions from each mode are superimposed, the scattered radiation will interfere either destructively or constructively in a given direction, leading to strong directional scattering in either the forward direction or in both the forward and backward directions. It is also possible to for scattering from different modes to suppress all forward scattering (second Kerker condition) but due to the symmetry conditions of the system this is only achievable far from a resonance, and the scattering is comparatively weak[12]. Depending on the selection of the modes from which radiation interferes, the directionality of radiation can be greatly enhanced, as shown in the finite element simulation results in Figure 2.

Figure 2: Showing the scattering cross section (normalized to the geometric cross section of the particles $A_p$) for a 12.5 mm radius dielectric sphere with a permittivity $\varepsilon=10.5$ and a loss tangent $\delta=0.001$ with varying radius ($r_i$) of (a) air-filled/hollow and (b) metallic core. The inset shows a cross section of the geometry. Each design shows three overlap points between different modes, and the 3D farfield scattering pattern for each combination is shown beneath.
separated. However, as Fig. 1c shows, the electric near fields of the electric and magnetic modes are quite distinct, with electric modes having a significant field component at the center of the sphere and magnetic modes being more confined to the outer rim. Therefore, as proposed theoretically by Liberal[15] and Naraghi[16], altering the refractive index in the central region will cause the electric modes to shift in frequency to a greater extent than the magnetic modes. This can be seen in Fig 2a, where the insertion of an air core in a high permittivity sphere leads to a blue-shifting of the electric superbackscattering[17], but this is not possible with a metal core due the fact that all modes are shifting simultaneously. Each mode pairing gives a dramatically different scattering pattern, with higher order pairings giving increasing directionality, as predicted by Liu for core-shell nanoparticles[6]. This control over choice of stacked modes has applications wherever one wishes to control the scattering or emission of a dielectric resonator. We will now discuss two of the most prominent examples of this case at microwave frequencies – controlling the radar cross section (RCS) of an object, and creating directional antennas.

The addition of a metallic core in this region can also be seen in Fig. 2b to have a strong impact on both mode families. Previous reports describe mode stacking by matching the plasmon modes of a metallic core to the magnetic modes of a dielectric shell[5], [6]. However at microwave frequencies the core does not support a plasmon mode, and as can be observed in Fig. 2b, increasing the metal core diameter can lead to a redshift in the electric modes and a blueshift in the magnetic until they overlap. Thus in this case we are observing exclusively the stacking of modes of the dielectric shell, where the different charges and currents induced in the metal core lead to a different shift for each mode, making this distinct from the behaviour of materially similar nanoscale structures.

As each mode has a different electric field distribution (Fig. 1c), each will be affected differently by the addition of a core, and so different modes will overlap at different frequencies. For the case of the hollow core, it has previously been observed that due to the broad nature of the lower-order modes it is possible to overlap multiple modes simultaneously, leading to multi-band superbackscattering.

Control of the RCS of small objects is key in fields such as drone detection, autonomous vehicles and cloaking. We carried out an experimental demonstration of the effect of mode stacking to both increase and decrease the RCS of a 12.5 mm radius sphere milled as two hemispheres from premix 1050 (permittivity in the low GHz regime of $\varepsilon = 10.5$, loss tangent, $\delta = 0.001$)[23]. A 5 mm radius cavity was chosen to maximize backscatter while a 4mm radius cavity coated with conducting silver paint (acting as a metallic core) was chosen to minimize backscatter. The samples are shown in Fig. 3a. Samples were placed in an anechoic chamber (Fig. 3b) and were mounted on Rohacell 31HF foam, chosen for its extremely low relative permittivity ($\varepsilon = 1.04$). Microwave radiation was provided via an Anritsu MS46122B VNA and a DP240-AB Dual-polarisation horn antenna from Flann Microwave. The RCS is measured quasi-monostatically using a second antenna, located adjacent to the emitting antenna. All measurements are calibrated using a 12 mm radius brass sphere and a time gating function was utilized to minimize unwanted reflections.
Excitation is provided from a lumped port which creates a symmetry plane for the resonant modes on an infinite, previously perfect electric conductor (PEC) ground plane, allowing then to be easily fed via a coaxial probe as shown in Fig. 4a. Whilst the hemispheres are now in the forward direction, as seen in the radiation plots in Fig. 2. For an air core, the mode overlap increases scatter in both the forward and reverse directions and a 5mm radius air core can improve the RCS by a factor of 1.5 around the peak at 5.1 GHz. A previous study demonstrates that similar enhancements in RCS are possible about multiple peaks simultaneously[17].

The ability to utilize a core-shell structure to achieve mode overlap can also be used to engineer the emission pattern of an antenna. In this case we slice the spheres in half, and place the hemispheres on top of a ground plane, allowing them to be easily fed via a coaxial probe as shown in Fig. 4a. Whilst it must be noted there have been several previous works discussing core-shell hemispherical DRA's[24]–[28], the focus of these has generally been to broaden the bandwidth of such resonators, and the utility of this system to control the directivity of a DRA has yet to be fully explored.

Figure 4 shows an Ansys HFSS simulation of a hemispherical antenna design used to achieve bidirectional emission by coupling to the ED & MQ modes simultaneously. This is achieved by simply optimizing \( d_f \) the position of a 4.8 mm long, 1.3 mm diameter feed probe cut from a coaxial structure corresponding to a standard SMA connector (PTFE-filled coaxial cable with a diameter of 4.1 mm). The properties of the hemispheres are identical to the spheres used previously except that they are now cut in half and modelled on an infinite, perfectly conducting (PEC) ground plane, which creates a symmetry plane for the resonant modes. Excitation is provided from a lumped coaxial waveguide port at the bottom of the probe. It can be observed that when the feed is at the center of the hemisphere (\( d_f = 0 \) mm), there is only a single S11 dip at 4.88 GHz, which corresponds to the excitation of electric dipole, as can be seen from the corresponding emission pattern in Fig 4c. When the feed is moved near the edge of the hemisphere, (\( d_f = 8 \) mm), it can be seen that there are two S11 minima at 3.45 and 5.05 GHz. The higher frequency peak can be seen to be quadrupolar in nature from the corresponding emission pattern in Fig 4c, and matches the MQ mode in frequency in Fig. 2a, whilst the lower peak corresponds to the MD mode. This is to be expected as the currents in the probe must match the fields one wishes to excite at the location of the feed. Therefore a coaxial probe feed placed at the center of the hemisphere, with a ground plane beneath providing a PEC symmetry plane will not match well to the fields of magnetic resonances and will predominantly excite electric modes. Near the edge the reverse is true, and the probe excites mostly magnetic modes.

As the feed position is moved across the radius of the hemisphere, changing \( d_f \) can be observed to lead to excitation of both the ED & MQ modes. When (\( d_f = 4 \) mm), both modes are excited equally, and the bidirectional emission pattern seen for ED+MQ mode overlap in Fig. 2a is once again observed. The impedance bandwidth is 0.24 GHz, or 4.75 %.

Unidirectional emission can be achieved using a metallic core, as shown in Fig. 5. In this instance, a 6 mm long, 1.8 mm diameter feed probe is fixed at \( d_f = 10 \) mm and the radius...
of the metallic core, \( r_i \), is altered in order to drive the ED & MD modes together both spatially and in frequency. It can be seen that for \( r_i = 5 \) mm, which corresponds to the ED+MD overlap in Fig. 2b, both the S11 and the directivity are maximised, producing unidirectional emission with an impedance bandwidth of 0.31 GHz or 7.95% and a directivity of 5.4 dBi.

3. Conclusions

In this work we have demonstrated the versatility of mode stacking in high symmetry dielectric particles such as a core-shell sphere, both for maximizing and minimizing the radar cross-section of the particle, and for defining the directivity of a dielectric resonator antenna. We have demonstrated that RCS can be maximised or reduced to almost zero at a given frequency by utilizing an air-filled or metallic core to stack modes whose emissions sum constructively or destructively respectively in the backwards direction. We discuss how the same physics can be used to design antennas where multiple modes are driven simultaneously at the same frequency, allowing for bidirectional or unidirectional emission. Combinations of higher order modes will enable even more directional beams and a greater variety of emission patterns.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References


Advances in Metamaterials
On-Demand Electrical Tuning of Metasurface with Complex Modulation for Arbitrary Wavefront Shaping

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Abstract

We present an ultrafast, electrically-tunable, 50-channel metasurface array that can generate arbitrary phases and amplitudes of light in reflection and achieves on-demand beam steering. The individual metasurface of the demonstrated array consists of an index-modulating indium tin oxide layer sandwiched between the individually-addressable top and bottom electrodes. Applying separate biases to the electrodes modulates the charge concentration in the ITO layer, which allows independent control of the complex reflection coefficient and consequently the phase and amplitude of reflected light.

1. Introduction

Reconfigurable metasurface is an emerging research field where a diverse set of optical responses and specific optical functions could be realized through post-fabrication tuning of metasurfaces [1]. A myriad of unprecedented phenomena and applications, such as wide-angle dynamic holographic display, wearable displays, virtual/augmented reality, and light detection and ranging (LiDAR), could stem from tunable metasurfaces [2]. Various materials and configurations have been explored to modulate the amplitude, phase, and polarization of light, including the transparent conducting oxides, III-V semiconductors, graphene and 2-dimensional materials, and liquid crystals [3–5]. However, limited operational speeds and phase range below 360° as well as undesired coupled modulation of the phase and amplitude continue to remain issues for realizing practical devices.

Here, we demonstrate an ultrafast, electrically tunable metasurface that can independently control the phase and amplitude of light in reflection in the infrared regime (Fig. 1). The metastructure is composed of an indium tin oxide (ITO) as an intermediate index-modulation layer with the top plasmonic Au antenna and the bottom Al mirror (the inset of Fig. 1), which also serve as the top and bottom electrodes. Electrical biases applied to the top and bottom electrodes lead to accumulation and depletion of charges in the intermediate ITO layer, which contributes to the change of the ITO layer’s dielectric function and refractive index. Separately controlling the top and bottom biases facilitates resonance-wavelength shifts and transitions in coupling-dynamics, enabling arbitrary adjustment of the real and imaginary parts of the reflection coefficient (r). Building on this principle, we have implemented an individually-addressable 50-channel antenna array and demonstrated beam steering with the side mode suppression ratio of 2.7 dB. The field of view measured 8° while the switching speed reached ultrafast 5.6 MHz per channel.

2. Effect of electrical bias and wavefront shaping

The ITO film plays the role of an electrically-tunable index-changing layer. The relative electric permittivity of ITO is given by the Drude’s model as follow:

$$
\varepsilon_{\text{ITO}} = \varepsilon_{\text{inf}} - \frac{\alpha_{p}^2}{\varepsilon_0(\omega - \Gamma)},
$$

where

$$
\alpha_{p} = \sqrt{\frac{N e^2}{m^* c_0}}.
$$

Here, the effective electron mass m*, the scattering rate Γ, and static permittivity ε_{inf} were set at 0.35*m_e, 1.0×10^{14} rad/s, and 3.9, respectively, for the full-field simulation.
Electrical gating leads to the formation of an accumulation layer or a depletion layer at the interface between the ITO layer and the neighboring insulator (gate oxide) layers, which is expressed as a change in the carrier density $N$. In Figs. 2(a) and 2(b), we show the real and imaginary parts of the dielectric constant as a function of the wavelength for three cases of $N$. The green line corresponds to the no-bias case while the red and blue lines are for the depletion ($N = 0$) and accumulation cases ($N = 6.0 \times 10^{20}$/cm$^3$), respectively. The initial doping level of the ITO was assumed to be $N = 4.0 \times 10^{20}$/cm$^3$. We note that a gigantic change exceeding 1 occurs in the real part of the permittivity (Fig. 2(a)). This leads to the blue- and red-shift of the resonance in the accumulation and depletion cases, respectively. In addition, the accumulation or depletion lead to a substantial increase or decrease in the dissipation (or the internal loss), which is represented by the rise or drop of the magnitude of the imaginary part (Fig. 2(b)). Consequently, the resonance dynamics undergoes transition between the under- and over-coupling regimes and so does the values of the reflection coefficient’s real part and the reflected amplitude. By separately controlling the resonance shift and the coupling dynamics, we achieve complete modulation of the real and imaginary parts of the reflection coefficient and thereby the phase and amplitude of reflected light.

To demonstrate the concept, we fabricated an individually-addressable 50-channel-array. Each channel includes a metasurface with the ITO layer sandwiched between the top Au plasmonic antenna and bottom Al mirror (the inset of Fig. 3(a)). The thickness of the ITO layer is 5 nm, and that of the top & bottom oxide insulators (HfO$_2$) is 8 nm. The antenna width is 185 nm, and the spacing (edge-to-edge distance between the neighboring antenna) is 215 nm. Figure 3(a) shows experimentally measured phase and amplitude of reflected light as a function of voltage combinations $(V_s, V_b)$. Please note that we can achieve 360° phase change while sustaining a pseudo-constant amplitude. Using the 50-channel-array, we have demonstrated beam steering (Fig. 3(b)). The sawtooth-shaped gradient phase profile is encoded and applied across the array. The intensity profile of the far-field shows that the main beam around $-4^\circ$ exhibits the highest intensity, and the side mode suppression ratio is around 2.7 dB, which has been the highest contrast ratio reported so far, according to our knowledge.

Figure 2. Electrical permittivity (dielectric constant) of indium-tin-oxide (ITO) as a function of applied bias. (a) Real part. (b) Imaginary part with the sign reversed.

Figure 3. (a) Experimentally measured phase and amplitude of reflected light as a function of $(V_s, V_b)$. Inset: transmission electron microscopy image showing the cross-sectional view of an antenna (scale bar: 50 nm). (b) Intensity profile of the steered beam.

3. Conclusions

In summary, we have demonstrated an electrically tunable metasurface array that adjusts the reflection coefficient’s real and imaginary parts as demanded; allows complete and independent modulation of the phase and amplitude of reflected light; and achieves on-demand beam steering with superb performance metrics. We believe that our work may shed light on the implementation of future applications such as LiDAR, holographic display, and free-space optical communications. In the presentation, we look forward to discussing the design, fabrication, testing, and application demo of our device.

References

Soft Matters for Extremely High-Index Meta-Optics

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Abstract

Conventionally, meta-optics has benefitted from the rapid advances in semiconducting processing such as lithography and lift-off/etching of hard materials. Here, I’ll introduce that it is time to widen our view of materials and relevant processing for meta-optics. Especially, colloidal self-assembly can extremely increase the polarization of effective medium and resultant refractive index.

1. Introduction

In general, the range of light-matter interaction can be mainly defined by two factors: (i) compositional and (ii) morphological complexities [1]. From naturally occurring materials, we already have a wide range of compositional options, such as metals, organic polymers, oxides, and fluids. By contrast, the morphological complexities, which have been defined by conventional semiconductor processing, were mainly limited to the 2D or pseudo-3D, as lithography is intrinsically compatible with 2D rather than 3D patterning. This limited morphology cannot be matched with what is accessible from the naturally occurring photonic systems (e.g., 3D stacked cuticle arrays on a curved surface) (see Figure 1).

This limited control over morphological complexity in turn restricts the accessible range of light-matter interaction from the lithographically defined man-made system. In this talk, I’ll briefly introduce how soft matters and relevant assembly strategy can address this limitation of semiconducting processing with a distinct example of “meta-optics”. Especially, this argument on the importance of “soft meta-optics” will be discussed with the example of achieving extremely high electrical polarizabilities and effective refractive index of optical metamaterials.

2. Achieving Extreme Polarization via Soft Processing

At microwave and terahertz, semiconducting processing, jointly consisting of photolithography, evaporation, and selective etching, can lead us to develop the metamaterials (also meta-surfaces). However, a direct translation of this monolithic lithography into the fabrication of optical metamaterials is still challenging [1]. Particularly, to achieve the extreme electric/magnetic polarizabilities at the optical regimes, meta-atoms need to be organized with a few nanometer-gaps, while simultaneously maintaining 2D/3D structural complexity. Furthermore, these stringent structural criteria should be fulfilled over the large areas. These requirements for extreme meta-optics would be difficult to achieve with conventional lithographic approaches, whereas soft matters and their self-assembly can provide a viable route for addressing this issue.

2.1. Design of self-assembled ultrahigh-index optical metamaterials

According to the macroscopic Maxwellian descriptions, the key to success in achieving unnaturally high refractive index (\(n\)) is a maximizing electric polarization (\(P\)), while simultaneously minimizing diamagnetism (\(M\)). This can be achieved by the close packing of electric meta-atoms into a relatively thin layer. In particular, the induced electric dipoles (EDs) and resultant P can be boosted via capacitive coupling between electrical meta-atoms [2],[3]. Therefore, the distance between electric meta-atoms should be small as possible to maximize capacitive coupling and resultant \(P\).

The lithography can readily define the sub-100 nm-scale individual meta-atoms made of metals or semiconductors. However, the attaining sub-10 nm-gap over the large area is not easy-to-craft architectures for lithography especially at the university level. In contrast, the currently accessible

![Figure 1: Complexity in morphology and composition in natural and man-made material system [1].](image-url)
colloidal self-assembly can allow us for achieving this sub-10 nm-gap in a versatile way.

For example, the chemically synthesized, single crystalline gold (Au) colloids can be self-assembled into closely packed 3D and 2D superlattice via spontaneous entropic-packing (entropic self-assembly) [4],[5]. More critically, the gap between Au colloidal particles can be reduced within sub-5 nm via this versatile packing. This is because the chemically synthesized Au colloids are intrinsically encapsulated by 1~2 nm thick organic ligands.

As a result, incoming visible and near-infrared (NIR) light can be resonantly squeezed between Au colloids via the strong coupling of the induced ED, P and resultant n of this effective medium can be unnaturally increased beyond 10 (see bottom panel of Figure 2). Furthermore, this accessible n can be widely tuned simply by control over the gap. This can be achieved by the controlling volume fraction of Au colloids.

2.2. Synthesis, Assembly, and Achievement of High-Index

By using the rationally designed synthetic route, we successfully synthesized the highly uniform and precisely shaped Au colloids with sufficiently high yield, as shown in Figure 3 [6]. Then, these Au colloids were assembled into the closely packed superlattice. It turned out that the accessible metallic nanogap was in practice reduced to 4~5 nm, which would be difficult to achieve with lithography. As a result, unnaturally high refractive indices of 6.4 and 4.5 were achieved respectively at the resonant and non-resonant regimes, which correspond to NIR and mid-IR wavelengths [7]. To the best of our knowledge, these n values are among the highest.

3. Conclusions

Soft self-assembly of colloids have enabled an increase in effective refractive index beyond naturally available regimes at optical frequency, which could revolutionize various optoelectronic device (e.g., solar cell) [8].

Acknowledgements

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References

Metasurface for on chip nanophotnics

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Abstract
Metasurface has been drawn great scientific and practical interests due to its potential applications in novel optical devices. In this work, we build the designing strategy of metasurfaces for the applications in chip scale devices which feature effective spectral sorting on the nano-scaled photodetection systems. The working principle of designed metasurface is analyzed by coupled mode theory for efficient sorting functionalities. Furthermore, we show the electrical tuning of metasurface for the dynamic control of optical spin using the transparent conductive oxide combined with plasmonic metasurfaces.

1. Introduction
Manipulating the flow of light in nanoscale has been of great interests during the past decades in the field of nanophotonics. It is especially important in the development of optical devices in which the mismatch between optical and electronic sizes is considered as the crucial bottlenecks in realizing scaling down of optical components and integrating with electronic components. Recent progress on the development of nanophotonics has shown the novel control of light in metasurfaces as the light passes the ultrathin layer of sub-wavelength, nanostructured materials. Metasurface designed in metallic nanostructures that supports plasmonic resonances and promotes light matter interaction shows the unprecedented control of the propagation direction of light as the light passes through the film with the thickness approximately 20 times less than the wavelength of light [1]. Additional works and demonstrations of light matter interaction in metasurfaces show the novel control of the wavefronts of light that forms diverse optical response including the designed holographic images and vectorial control of transmitted light [2-4].

Very recently, metasurfaces designed by the semiconductor nanostructured has drawn particular interests in practical perspective for the applications in optical sensors. Compared to the plasmonic resonance that inevitably induces the heat loss, Mie resonance in dielectric nanostructures show negligible ohmic loss, and as such, dielectric metasurfaces shows the improved efficiency in transmission/reflection or other general light matter interaction including spin and wavefront control. Moreover, we consider the optical property of metal naturally reflects the light whereas the optical property of dielectric naturally confines the light due to its high refractive index. This leads to the strong light matter interaction in high refractive index materials that potentially increases the efficiency of metasurfaces. Moreover, absorbed light in semiconductor materials generated photo-carriers that can be extracted as electrical currents, which can be combined with electronic devices for next generation optoelectronics with novel functionalities that has not shown in conventional devices.

2. Discussion
In this work we leverage the distinct optical properties of metal and semiconductor nanostructures to develop the metasurface for the applications in optical devices. We will demonstrate how the metasurfaces can be designed as the photodetectors based on the coupled mode theory. Systems with two resonances are described as following equation.

\[
\frac{dA_1}{dt} = (j\omega_1 - \gamma_1)A_1 + (j\omega_1 - \gamma_0)A_2 + \kappa_1 S^+ \\
\frac{dA_2}{dt} = (j\omega_2 - \gamma_2)A_2 + (j\omega_2 - \gamma_0)A_1 + \kappa_2 S^+ 
\]

where \(A_n\) denotes the amplitude, \(\gamma\) denotes the loss by absorption (a) and radiation (r) respectively. Typically, multi-resonant systems that interact with free space (open system) shows diverse unprecedented spectral properties in optical absorption, transmission and reflection by its amplitude and phase. We found that the multi-resonant systems that drive strong light matter interaction in free-space shows the strong absorption and suppression of light. When two systems are spectrally spaced in very closed separation (~40nm), the spectrum features asymmetric lorentzian shape similar to the fano shape. Such a spectral feature and condition is found to be magnified as the two systems are over coupling to the incident light, whereas the under coupling of light shows the spectral shape getting closer to the symmetric lorentzian shape. Based on the observed features and working principles, we designed the semiconductor based metasurface photodetector that functions as efficient spectral sorting in three colors for the detection of red, green and blue color for image sensor applications. We found that distinct three meta atoms spaced in subwavelength scale show the efficient color sorting as their coupling to incident light becomes significant. Based on the reciprocity, strong coupling of incident light in resonant system means the strong radiation of coupled light. Such radiated light from each meta atoms strongly interacts with each other and naturally enhances or suppresses the
resonance when the other meta atoms show suppressed or enhance light matter interaction respectively. Furthermore, we found that the resonance in metasurfaces can be tuned by combining meta-atoms with transparent conductive materials including ITO whose optical properties can be electrically tunable. Based on the drude model, plasma frequency of ITO material can be dynamically tuned as the band-bending at the interface of ITO is controlled by the applied voltage. Dynamic control of plasma frequency leads to the control of refractive index in ITO layers that interacts with meta atoms. Such interaction results in the tuning of resonances and tuning of amplitude or phase of light. Based on the observed phenomena, we experimentally prove that the electrical tuning combined with metasurface is able to control the phase dynamically from 0 to 180 degrees. Considering that the spin condition of incident light determines the response of transmitted light in diverse metasurfaces and other nanophotonic systems, the proposed concept of dynamic phase control in 180 degrees can be effectively applied in multi-stacked metasurface based optical systems.

3. Conclusions

Based on the coupled mode theory, working principle of metasurfaces for effective spectral sorting and polarization control is elucidated, in which the condition between under- and over-coupling determines the functionalities of the designed metasurface. Designed metasurface has potential applications in diverse optical devices including nano-scaled photodetection systems and spatial light modulator.

References

Elastic Metasurfaces tailoring reflections and refractions

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Abstract
In this presentation, recent researches on elastic metasurfaces, thin artificial surface that can tailor elastic waves as desired, will be introduced. First, the reflection-type elastic metasurface will be focused, and a new idea of transmodal elastic metasurface will be introduced. After that, the refraction type elastic metasurface that can control the transmitted waves with a single doubly-negative unit will be explained. From these basic results, various new applications such as vibration and ultrasonic devices are expected.

1. Introduction
As the advances in electromagnetic metamaterials have opened the new field of elastic metamaterials, recent advances in electromagnetic metasurface give rise to the researches on elastic metasurfaces these days. Elastic metasurfaces are the artificial surfaces consist of the subwavelength structure, similar to electromagnetic metasurfaces. The difference is that elastic metasurfaces consider elastic waves, which is based on its unique tensor physics so that both the longitudinal and shear wave exists. Due to the physical difference, researches on elastic metasurfaces should be based on its own physics dealing with tensor variables and various mode-related phenomena. Fortunately, recent studies have successfully demonstrated the fundamental physics and experimental realizations[1-2].

In the presentation, our recent researches on elastic metasurface, including the reflection and refraction types, will be presented. First, we will focus on the reflection type, the simple case. Starting from the generalized Snell’s law for elastic metasurface, we will introduce that the metasurface can be tailored to perfectly transfer the longitudinal wave into the shear wave, i.e., the transmodal metasurface can be achieved[3]. After that, we will move to the refraction type elastic metasurface, tailoring transmitted waves. Here, the thickness issue of the elastic metasurface will be visited, and our proposition of “doubly-negative metasurface” will be introduced.

2. Reflection type elastic metasurface
Since elastic wave is based on its own tensor-based physics, elastic waves have various unique characteristics. One of

the most representative characteristics is the existence of the longitudinal and shear wave modes, and the mode conversion phenomenon between them. If elastic waves experience any reflection or transmission, the mode conversion takes place so that both the longitudinal and shear waves are generated, as shown below. This is same for the metasurface case – therefore, the previous theories for the generalized Snell’s law should be expanded to include the mode conversion as in Fig. 1 (a). We re-visited the generalized Snell’s law, and after the derivation with the classical elasticity, the generalized Snell’s law for elasticity is formulated.

(a) Elastic metasurface
(b) Transmodal metasurface

Figure 1: The idea of ‘transmodal metasurface’[3]

Based on the formulation, we will show the interesting application of the elastic metasurface – if the metasurface is properly designed, we found that there can be shear wave reflection only for the longitudinal wave incidence along any direction. In other word, the metasurface can be used to totally convert the longitudinal wave into shear wave – the
transmodal metasurface is possible. With the numerical and experimental supports, we will introduce our idea and possible application of the elastic metasurface.

3. Refraction type elastic metasurface

The refraction type elastic metasurface shares the same equation for the generalized Snell’s law with the reflection type. However, the refraction type elastic metasurface should also consider the wave transmission in addition to the phase shifts. Because of this constraint, previously proposed elastic metasurfaces usually consist of various cells along the propagating direction – unfortunately, this approach makes the metasurface very thick\(^\text{(2,3)}\). Unlike electromagnetic metasurface where the waves are highly affected by a thin surface, somewhat thick surfaces have been required to tailor elastic waves as desired, especially for the longitudinal wave whose polarization is same as its propagating direction.

Here, we will show that only a single cell can be used if the metasurface can be tailored to have negative parameters (density and stiffness). From the analytic investigations, we found that both the full transmission and full control of phase shift can be achieved when the metasurface can have double-negativity. Based on the previous research\(^\text{(4)}\), we designed new elastic metasurface whose effective parameters can be easily tuned from positive to negative values. With numerical simulation, it will be shown that various elastic wave tailoring can be achieved by using the doubly-negative elastic metamaterials.

4. Conclusions

In this presentation, various researches to tailor elastic waves with very thin metasurface are introduced. We expect that our research can be applied to various applications dealing with elastic dynamic motions, such as vibrations, ultrasonic applications, etc.

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References

Cyclic group symmetric metasurface for optical spin-dependent beam separation

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Abstract

Geometric phase is introduced when a cross-polarization scattering from nano-rod takes place. Here we introduce a cyclic group symmetric metasurface composed of tapered arc nano-rods and explore how azimuthal angular dependence of geometric phase determines the feature of spin-dependent beam separation.

1. Introduction

Vortex beam carries orbital angular momentum associated with topological charge. There are several means to generated vortex beam. Differently from refractive optics employing a set of cylindrical lens or spiral phase plate, spin-to-orbital momentum conversion (SOC) can utilize a geometric phase or Pancharatnam-Berry (PB) phase introduced in a cross-polarization scattering from nano-rod. In Poincaré sphere the solid angle subtended by polarization states of input beam and cross-polarized output beam corresponds to the geometric phase introduced. Instead of a uniform thickness nano-rod, a tapered arc nano-rod provides a a non-constant azimuthal gradient of geometric phase $\nabla_\phi \Phi_{PB}$. Here we investigate how the feature of spin-dependent beam separation in vortex beam generation is related to the symmetry properties of cyclic group symmetric metasurface. Different sizes of TA are arrayed in a circle to obtain metasurface possessing a point group symmetry of cyclic symmetry of $C_{nh}$, and experimental measurement of vortex beam profiles from cross-polarization scattering of circular-polarized beam from $C_{nh}$ TA-CGSM is performed and a detailed theoretical analysis is carried out.

2. PB phase from circular arrays of nano-rods

Linear array and circular array of nano-rods are displaced in Fig. 2 (a) and (b). Beam deflection from a linear array and vortex beam generation from a circular array via SOC are shown in in Fig. 2 (d) & (e) and (f) & (g), respectively. Polarization states of cross-polarization scattering are plotted on Poincaré sphere in Fig. 2 (c). Solid angle subtended by two meridians of cross-polarization scatterings from two neighboring nano-rods is a constant, resulting in a circular trajectory of polarization states from near the north-pole down to near the equator. This leads to $\Phi_{PB}$ having a constant azimuthal gradient of $\pm 2$. On the other hand, when scattered from a tapered arc nano-rod, $\Phi_{PB}$ having a non-constant azimuthal gradient. That is, $\nabla_\phi \Phi_{PB}(\phi)$ depends on the azimuthal angle $\phi$, and we can decompose the geometric phase $\Phi_{PB}(\phi)$ as a sum of constant and non-constant azimuthal gradient terms,

$$\Phi_{PB}(\phi) = \Phi_{PB}^{(0)}(\phi) + \Phi_{PB}^{(1)}(\phi),$$

(1)

with $\Phi_{PB}^{(0)}(\phi)$ having constant azimuthal gradient $\nabla_\phi \Phi_{PB}^{(0)}(\phi) = \pm 2$.

3. Fabrication of cyclic group symmetric metasurface

In Fig. 2 is displayed scanning electron microscope (SEM) image of metasurface composed of a tapered arc nano-rod belong to $C_{n1}$ cyclic group. Metasurfaces were fabricated on 1mm thick round borosilicate glass substrates with a diameter of 25mm (WBO-215 from UQG Optics).
First, after cleaning substrates 60-70 nm thick layer of e-beam resist (PMMA diluted in ethyl-lactate, AR-P 679 from All-Resist, Germany) was spin-coated onto the clean substrate surfaces at a rotation speed of 6000 rpm. Then, the e-beam resist underwent a soft baking process, and the second, conductive resist was spin-coated on the e-beam resist (SX AR-PC 5000/50.1 from All-Resist) and baked for 2 min at 85°C. Pioneer system (from Raith, Germany) equipped with a field emission electron gun was used for EBL patterning. We used the e-beam acceleration voltage of 20 kV, beam current of 0.016 nA, and aperture of 7.5 m. The working distance was about 5 mm.

Each sample contained a design of multiple metasurfaces organized in a matrix with a pitch of 2 mm in order to prevent eventual interactions during optical measurements. We slightly varied the EBL exposure dose in order to finely tune the width of individual features constituting the CGSMs. In the matrix rows, the nominal exposure dose was increased from 130 to 180 μC/cm², and the order of different metasurfaces increased from \( C_{1h} \) to \( C_{6h} \) in the matrix columns. PMMA is a positive resist, and the exposed resist areas are then easily dissolved in a corresponding solvent during the development step. After exposure, the conductive resist layer was removed with deionized water. The samples were then developed for 60 s in a commercial solution (AR 600-55 from All-Resist) containing a mixture of methyl isobutyl ketone (MIBK) and IPA. The development was stopped in pure IPA bath and the samples were dried under nitrogen flow. Third, a 2-3 mm thick chromium seed layer and 27 nm thick optically active gold layer were successively evaporated under vacuum (Auto 306 tool from Edwards). The thickness of deposited metal was monitored in situ using a quartz crystal microbalance. A lift-off process in ethyl-lactate in an ultrasonic bath was used to remove the e-beam resist as well as the excess of gold and chromium in the sample areas which were not exposed to the electron beam during EBL. Finally, the samples were rinsed in deionized water and dried under nitrogen flow.

After fabrication of the samples, the total thickness of deposited metal layer (30 nm) was confirmed by contact mechanical profilometer measurements (Dektak XT, Bruker, Germany). Then, the samples were characterized by optical microscopy as well as by SEM using the same Pioneer system as for EBL. All the metasurfaces were verified one by one by SEM observation in order to check for eventual (very rare) defects appearing during the lithography or lift-off steps. The sizes of individual nanofeatures were measured from SEM images taken at a low acceleration voltage (3 kV) in order to decrease sample charging. Quick optical microscope observations were performed using Nikon optical microscope at Planete.

4. Results and Discussion

Experimental measurement of spin-dependent beam separation is performed at a propagating distance of \( D = 50 \text{ mm} \), which gives the transverse shift of \( \Delta = 2 \times 0.02 \times \sigma \times D = 2 \text{ mm} \) for 1310 nm incidence beam wavelength. The vortex charge of cross-polarization scattering beam from \( C_{6h} \) metasurface is identified by an interference pattern between scattering vortex and incidence Gaussian beams. Counter-clockwise and clockwise twisted fringes confirmed topological charges of \( l = 2 \) and \( l = -2 \) of \( I_{+} \) and \( I_{-} \), respectively.

Spin-dependent beam separation was analyzed in terms of partial-wave expansion, azimuthal interference, and a non-constant azimuthal gradient of geometric phase \( \nabla_{\phi} \Phi_{PB} \). It is found that odd- and even-number group orders \( n \) of cyclic group \( C_{nh} \) plays an important role in giving rise to the beam separation profile, and a wavelength dispersion of spin-dependent beam separation of vortex beam indicated that there is a photonic spin Hall effect.

5. Conclusions

By introducing a tapered arc cyclic group symmetric metasurface, the details of optical spin-dependent beam separation in spin-to-orbital angular momentum conversion are investigated. Presence of non-constant azimuthal gradient of PB phase is found to be responsible for azimuthal interference pattern in vortex beams with asymmetric helical wavefront. By identifying the role of non-constant azimuthal gradient of PB phase in giving rise to spin-dependent beam separation, spatial separation and vortex beam profiling are achieved in a controllable manner.

Azimuthal interference pattern in vortex beams with asymmetric helical wavefront found to be related to symmetry property of cyclic group \( C_{nh} \), and group order \( n \) determines topological charge \( l \neq \pm 2 \) of additional vortex beams.

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Topology in photonic crystals, metamaterials, and metasurfaces: physics and design
Broadband Optical Modulation via Dual Epsilon-Near-Zero Modes

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Abstract
Epsilon-near-zero (ENZ) modes have attracted extensive interests due to its ultrasmall mode volume resulting in extremely strong light-matter interaction. However, the operation bandwidth is usually limited by the ENZ wavelength range. In this paper, broadband optical modulation is demonstrated by dual ENZ modes in a TCO/dielectric/silicon nanotrench configuration. Different types of carrier accumulations in both silicon and TCOs give rise to the ENZ states at two wavelengths determined by the carrier densities.

1. Introduction

Ultrafast light modulation with a large contrast is desired for many applications such as optical communication, signal processing, etc. To achieve this goal, it is important to reduce the device size and maintain the strong light matter interaction simultaneously. However, the size of optical mode field is determined by the refractive index distribution and usually diffusion limited. Although metallic structures supporting plasmonic resonances can break this limit and suppress the mode field down to tens nanometers scale, the loss increases greatly. Electrically tuned Epsilon-near-zero (ENZ) effect is a promising method to remarkably enhance the light-matter interaction for optical modulation [1]. Based on the electromagnetic field continuous condition at an interface, the material with the ENZ effect in principle has unlimited field concentration. Recently, this effect has been observed in transparent conductive oxides (TCO) such as ITO, ZnO and CdO. Unity-Order index change was obtained in ITO at visible frequencies by electrically tuning the Au-ITO-SiO2-Au stack [2], where the electric field is concentrated around the ITO/SiO2 interface due to the ENZ effect in ITO under bias. Although this modulation behavior was observed in Si [3] and metal [4], it is much more prominent in TCOs due to its large tunability [1], for example, ultrafast third-order nonlinearity [5], ultrafast switching [6,7], and Gbps digital modulation rate [8]. The drude model shows that the ENZ wavelength associates with the carrier concentration, i.e. the bias. As a result, the ENZ modulation is intrinsically efficient only in a narrow bandwidth, which is not ideal for many applications.

In this paper, we observed the dual ENZ mode modulation in a TCOs/dielectric/silicon nanotrench configuration [9]. Different types of carrier accumulations in both silicon and TCOs give rise to the ENZ states at two wavelengths determined by the carrier densities at positive or reverse bias. Such spatially separated absorption modes in two ENZ materials together with the SIS heterojunctions provide unique light modulation properties. By carefully tuning nanotrench structures and doping concentrations to efficiently couple optical absorption and electrical capacity in a same SIS configuration, a broadband light modulation with a Δf/f of 60% was demonstrated benefiting from the combination of dual ENZ modes confined in silicon and TCOs accumulation layers respectively. Furthermore, a simple EMT method together with ellipsometry analysis was developed to accurately and rapidly predict the modulation properties.

2. Results and Discussion

As shown in Fig. 1, the proposed spatial light modulation scheme is based on a semiconductor-insulator-semiconductor (SIS) nano-capacitor, in which the high aspect Si nanotrench array with an ultra-thin conformal coating of high k insulator (HfO2) assumes to be completely wrapped by Al-doped ZnO (AZO). Under external voltage biasing, the capacitor encounters charge accumulation at both sides of the SIS junction. With sufficient high carrier density, dual ENZ confinements can be anticipated in the nanometer thin layers which result in substantial E-O absorption along the sidewall of the nanotrench. Regarding on the gradual and continuous spatial variation of surface
stepwise profile

two

modulation is observed as shown in Fig. 1. The simulated carrier densities at various bias. Simulated $r$ (b) Figure 2

spectrum at various bias by EMT and FDTD methods. The inset shows of the electric field intensity distribution of the ENZ mode at 4V bias. (c) The calculated reflection spectrum at various bias by EMT and FDTD methods.

charge profiles under quantum treatment, broadband modulation is observed as shown in Fig. 1c rather than the two separated modulation bands in Fig. 1b for the case with stepwise profile assumption. As shown in Figure 2b, the spectral modulation tends to operate in an ultra-broad wavelength regime rather than previously expected two discrete bands. In experiment, Al-ZnO was deposited on Si nanotrenches by pulsed laser deposition to ensure the coverage on the high aspect ration structure. Obvious light modulation was observed around 4μm with a bandwidth covering 2.5-5μm. A shape and large reflection dip located at the wavelength of 2021 nm and a small dip at 2650 nm were observed. These features originate from the ENZ absorption or ray destructive interference. Regarding on the high background carrier level ($3.3 \times 10^{20}$ cm$^{-3}$) of AZO, the SIS capacitor with thick cap atop of the nanotrench becomes more reflective at the mid-IR regime (roughly 60% of incidence sacrifices at first partial wave). Only a small portion of light can enter the nanotrench layer and response to the field-effect induced ENZ mode operating at same wavelengths, thus, resulting in unsatisfactory modulation efficiency. This highlights the importance of fine controlling the material’s background carrier concentration in our nanotrench or other non-resonance structures for pursuing high modulation depth.

References

Recent experimental and theoretical developments in synthetic dimensions including the frequency axis of light

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Abstract

The field of synthetic dimensions in photonics is under rapid development and is interesting to the broad community. Recent efforts on the synthetic space including the frequency axis of light have been largely explored with their linear properties. Moreover, we show the possibility of creating an effective nonlinear Bose-Hubbard Hamiltonian with local interactions along the frequency dimension. Our works trigger further interests in synthetic dimensions and point towards potential possibilities for manipulating internal degrees freedom of light.

1. Introduction

The physics of a photonic structure is commonly described in terms of its apparent geometric dimensionality. With the concept of synthetic dimension, it is possible to explore physics in dimensions that are higher than the physical dimension of the structure [1,2]. A variety of proposals for constructing the synthetic space including different degrees of freedom for photons, such as the frequency dimension [3-7], the orbital angular momentum dimension [8-10], and the modal dimension [11-13], have been studied, which show important potentials for further manipulating the light in versatile ways.

Here, we show our recent works in synthetic dimensions including the frequency axis of light. In particular, we show the topological effects in two independent synthetic dimensions [14]. Furthermore, we discuss the possibility of creating an effective Hamiltonian with only the onsite nonlinear interaction along the synthetic dimension [15]. Our works open an avenue pointing towards future explorations of synthetic dimension using the frequency axis of light in practical applications.

2. Results and Discussions

We summarize our recent experimental and theoretical researches on synthetic dimensions.

2.1. Experiment of constructing two independent synthetic dimensions in a single fiber resonator

In experiments, we construct a fiber ring as shown in Fig. 1, which construct a synthetic space including the frequency axis of light and the CW/CCW modes in the ring [14].

Figure 1: (a) A modulated fiber ring supporting two independent synthetic dimensions (b). (c) Measured chiral bandstructure and (d) the corresponding chiral current.
In the synthetic space, it exhibits nonzero effective gauge potential, which brings the synthetic Hall ladder. We measure the bandstructure by performing time-resolved transmission for CW excitation and show the chiral current versus laser-cavity detuning by using frequency- and spin-resolved heterodyne detection.

2.2. Theory of creating an Hamiltonian where the interactions are local in the synthetic space

We study a ring resonator with a modulator to create the synthetic dimension including the frequency axis of light [15]. Third-order nonlinear susceptibility is considered to create photon-photon interaction in the frequency dimension. By a careful design of the group velocity dispersion of the waveguide in the ring, we keep only the self-phase and cross-phase modulations in the system, and therefore, demonstrate a Bose-Hubbard Hamiltonian [see Fig. 2].

Figure 2: (a) Schematics of the model. (b) Distribution of the two-photon correlation probability along the synthetic frequency dimension.

In such proposal, we simulate the two-photon dynamics and hence achieve photon-blockade effects along the synthetic frequency axis of light.

3. Conclusions

In summary, we show our recent development in experiments of constructing two independent synthetic dimensions in a single optical resonator for the first time [14]. Many important physical phenomena including the effective magnetic gauge potential for light, the topological chiral one-way edge current, and also the synthetic Hall ladder. Moreover, from the theoretical perspective, we propose a technique to achieve an interacting Hamiltonian that contains only on-site interaction along the synthetic dimension [15]. Our works shows the possibility of studying a wide variety of physics associated to higher dimensions in simple systems by applying the concept of synthetic dimensions, which is of significant emerging interest in the field of topological and quantum photonics.

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References

Inverse design of metasurfaces and photonic systems for enhanced Raman scattering

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Abstract

We propose and investigate designs for nano-patterned surfaces and devices, tailored to maximize the surface enhanced Raman scattering (SERS) occurring from molecules placed near them. The designs are created using our extended version of a recently proposed approach [1], utilizing topology optimization as an inverse design tool. The modified approach takes additional limitations in the fabrication process into account in order to minimize the discrepancies between the design blueprint and the fabricated metasurface.

1. Introduction

In brief, Raman scattering is the result of an incident wave, oscillating at \( \omega_1 \), interacting with a molecule, which then emits electromagnetic radiation at \( \omega_2 \). The presence of nanostructures near the molecule can enhance the scattering effect by increasing the incident-wave absorption through a focusing effect and by increasing the emission through a Purcell effect. Work on deriving fundamental limits to the surface enhancement of Raman scattering (SERS) [2] revealed a vast potential for achieving improvements to SERS when comparing the performance of various conventional designs to these fundamental limits. Subsequently, in recent work [1] it was demonstrated that by utilizing topology optimization [3] it is possible to attain \( \sim 10^2 \times \) improvement in SERS compared to simple parameter optimized bowtie antennas when considering a two dimensional (2D) setting. In the present work we discuss the application of an extension of the work from [1] to the design of metasurfaces for SERS in a fully three dimensional (3D) setting. Further, we demonstrate the versatility of the method by applying it to different model problem configurations.

The talk will provide a brief introduction to the topology optimization method, an in-depth description of the design procedure, several examples of applying the proposed approach to 2D and 3D design problems, as well as preliminary experimental results.

Figure 1: Sketches of the design problems and model domains illustrating the design domain [gray], the molecule position [dark blue], the incident wave [green], the emitted wave (red) and the line/surface through which the emission is sought maximised \( [\Gamma_{out}, \text{purple}] \) or minimised \( [\Gamma_{NO}, \text{blue}] \). (A) Periodic surface. (B) Single device.

2. The Method

We simulate the Raman scattering phenomenon in the frequency domain as a two step process using the following model and appropriate boundary conditions (detailed in [1])

\[
\nabla \times (\mu^{-1} \nabla \times E_1(r)) - \omega_1^2 \epsilon(r) E_1(r) = f_1(r), \quad r \in \Omega, \quad (1)
\n\nabla \times (\mu^{-1} \nabla \times E_2(r)) - \omega_2^2 \epsilon(r) E_2(r) = f_2(r), \quad r \in \Omega. \quad (3)
\]

Here \( \Omega \) denotes the modelling domain shown in Fig. 1. \( r \) is the spatial coordinate vector, \( \delta \) is Dirac’s delta function with \( \mu \) and \( \epsilon \) being the magnetic permeability and electric permittivity, respectively. The electric field is given by \( E_i \). The angular frequency by \( \omega_1 \), and the excitation source by \( f_i \), \( i \in \{1,2\} \). Finally, \( \alpha = I \) denotes the polarizability tensor.

We seek to increase the Raman scattering from a molecule by tailoring the geometry of nanostructures (controlled through the field \( \xi(r) \)) near the molecule by maximizing...
\[ \Phi(\xi) = \Phi_{\Gamma_{\text{out}}}(\xi) = \int_{\Gamma_{\text{out}}} \langle \mathbf{S}_2(\xi) \rangle \cdot \mathbf{n} \, d\mathbf{r}. \]  

(4)

Here \( \langle \mathbf{S}_2 \rangle \) denotes the time averaged Poynting vector, \( \Gamma_{\text{out}} \) the surface through which the emission is sought maximized, \( \mathbf{n} \) is the outward pointing normal vector on \( \Gamma_{\text{out}} \). The figure of merit in (4) is maximized by systematically changing \( \xi(\mathbf{r}) \) using density based topology optimization. To minimize the discrepancy between the optimized design blueprint and the fabricated sample a filtering technique is employed to account for the slant angle observed in the physical samples (See Fig. 3D). This allows the design process to exploit the slant angle to create highly optimized designs rather than the angle leading to unwanted discrepancies between simulation and experiment.

The optimized design blueprints are fabricated using electron beam lithography using the metal lift-off method. The normal Raman and SERS spectra are recorded using a Raman microscope.

3. Discussion

As a simple 2D example we design a nanostructure operating at the wavelengths \( \lambda_1 = \lambda_2 = 532 \) nm, which controls the emission direction for a single molecule to maximize emission in the angular interval \( \theta \in [30^\circ, 120^\circ] \) centered at \( \theta_c = 75^\circ \), see Fig. 2. This is done by selecting \( \Gamma_{\text{out}} \) and \( \Gamma_{\text{NO}} \) appropriately, see Fig. 1B, and modifying the figure of merit to maximize the power fraction emitted in \( \Gamma_{\text{out}} \) relative to \( \Gamma_{\text{NO}} \) multiplied by the total power emission. Despite being sub-wavelength the optimized structure directs \( \sim 73\% \) of the emitted power through \( \Gamma_{\text{out}} \) which only covers \( \sim 25\% \) of all emission angles, while simultaneously maintaining the emitted power at the same level as the bowtie compared to the parameter optimized resonant bowtie structure from [1], i.e. \( P_{\text{total,optimized}} / P_{\text{total,bowtie}} \approx 1 \).

![Figure 2: Angular power emission profile for optimized (blue) and bowtie (orange) nanostructures.](image)

As a 3D example we apply the extended design approach to create a periodically-nano-patterned surface, designed to maximize SERS for a periodic array of molecules placed at the center of the unit cell, see Fig. 3A. The blueprint at the base of the designed nanostructure in the periodic unit cell is shown in white in Fig. 3A and the extruded structure with the enforced slant angle is shown in Fig. 3B. A fabricated sample is shown in Fig. 3C and 3D. By comparing the blueprint and sample, agreement in the geometries to within a few nanometers is observed.

![Figure 3: Top-down view of (A) Unit-cell blueprint at structures base (B) extruded blueprint, (C) 2x2 unit cells of fabricated sample. (D) Angled view of fabricated sample.](image)

4. Conclusion

The application of inverse design (topology optimization) is demonstrated to be a promising avenue for designing novel, highly-efficient, SERS systems with the opportunity for added functionality, such as directional emission. Something that is extremely difficult, if not impossible using conventional design rules and human intuition. Further, it is demonstrated that it is possible to account for fabrication constraints directly in the design process, thus minimizing discrepancies between the optimized blueprint and fabricated sample.

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References


Active optical metasurfaces based on VO$_2$ phase change materials

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Abstract
We report several active metasurface devices based on VO$_2$ hybrid metaatoms. We show several prototype devices for ultrafast optical modulation, optical switch and flexible active photonic device applications.

1. Introduction
Metasurfaces attracted great research interest recently. However, most metasurfaces reported so far are passive, showing fixed optical properties by design. Achieving active metasurfaces in the optical frequency is challenging yet highly desired for several important applications, such as optical switching, optical modulation and reconfigurable photonic devices. Several active photonic materials are proposed for active metasurfaces applications, such as phase change materials, epsilon-near-zero materials, liquid crystals, magneto-optical materials and two-dimensional materials. Among these materials, active metasurfaces based on vanadium dioxide (VO$_2$) show advantages of high modulation speed, low power consumption and ease for integration, which is promising for active metasurface applications.

2. Results and Discussion
In this talk, we report our recent progress in active metasurfaces based on VO$_2$ phase change materials. Using pulsed laser deposition and reactive ion etching, we fabricated VO$_2$ thin films, nanostructures and active metasurfaces. Phase change of VO$_2$ is observed under temperature, light or strain stimulus, leading to a drastic change of the optical properties of the metaatom in the near to mid infrared. We demonstrate several active metasurfaces based on VO$_2$.

First, we show ultrafast optical switches using Au/VO$_2$ plasmonic metasurfaces based on extraordinary optical transmission (EOT) effects and photon induced hot electron injection, as shown in Fig. 1. The devices show optical modulation on-off ratio up to 13.8 dB and insertion loss down to 3.3 dB at 2190 nm wavelength. In particular, by judiciously align the SPR (surface plasmonic resonance) wavelength to the pump wavelength of the femtosecond laser, the excited Au surface plasmon resonance at 800 nm is capable to switch-off the EOT effect at 2190 nm in 100 fs time scale. Compared to VO$_2$ thin film samples, the device also shows 50% power reduction for optical modulation.

Next, we demonstrate a tunable optical metasurface in the mid-infrared wavelength range based on Mie-resonance and localized surface plasmon resonance (LSPR) switching in Si/VO$_2$ nanodisks. By incorporating VO$_2$ in Si Mie resonators, we reduced the absorption loss of the metaatom, leading to efficient amplitude and phase modulation of the metasurface in 10 µm wavelength range.

Finally, we fabricated large scale VO$_2$ based active metasurfaces on flexible substrates using a water assisted transfer printing process, achieving flexible active metasurfaces adaptive to the curvature and optical properties of arbitrary substrates. Our work shows that VO$_2$ based active metasurfaces are promising candidates for fast, adaptive and energy efficient active photonic device applications.

![Figure 1: (a) Sketch of the Au/VO$_2$ based active metasurface. (b) SEM image and (c) surface morphology of the Au/VO$_2$ metasurface](image)

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Operator Bounds for Electromagnetic Power Transfer

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Abstract

We present a method for utilizing power transfer constraints on the electromagnetic scattering operator to set physical bounds on any single material design problem that can be framed as a net emission, scattering or absorption process. The technique is found to predictively quantify and differentiate the relative performance of dielectric and metallic materials for both far and near-field sources. The broad applicability of scattering theory means that similar application to acoustics, quantum mechanics, and other wave physics are likely possible.

In a recent series of articles [1, 2, 3], we have detailed how physically motivated algebraic constraints on the electromagnetic scattering $\mathcal{T}$ operator can be used to affix bounds on angle-integrated absorption, thermal emission, and near-field radiative heat transfer for any possible device geometry, i.e. bounds analogous to the blackbody limit for structures that violate the assumptions of ray optics (nanoparticles, thin films, photonic crystals, etc.). Here, we will summarize these findings and report recent extensions of the method to treat general power transfer interactions for general sources, including the incorporation of the full electromagnetic susceptibility $\chi$ via the conservation of reactive power. Particularly for small bounding volumes, this information can lead to massive (many orders of magnitude) differences in calculated performance limits between metals and dielectrics. We will also overview contemporary work in this rapidly developing area [4, 5, 6], describing how $\mathcal{T}$ operator constraints unify the two overarching strategies previously considered for developing limits on electromagnetic power transfer processes—modal decomposition (quasi-normal modes, Fourier and multipole expansions) [7, 8] and conservation principles [9].

For all application we have studied (far-field scattering, absorption and extinction cross sections, and thermal emission, as well as near-field radiative and extinction of a dipole source, and heat transfer across a nanoscale gap), $\mathcal{T}$ operator bounds have been found to be meaningful applicable (non-trivial) at all length scales and for all real materials. For instance, considering integrated absorption, they evolve smoothly from the volume scaling of absorptivity known to be achievable in the quasi-static regime to the area scaling (black body limit) of macroscopic bodies. Moreover, in the far-field, the predictions of ray optics (blackbody limit, geometric cross sections, etc.) are always asymptotically approached for any fixed value of the material figure of merit $\zeta = |\chi|^2 / \text{Im} [\chi]$ in the large domain limit, and for a domain of fixed size, enhancement is found to display an extremely weak sublogarithmically divergence with $\zeta$, as opposed to the quadratic divergence reported previously. $\mathcal{T}$ operator bounds have also been shown to be a useful method for rigorously proving and elucidating several facts previously suggested by inverse-design studies. For instance, in the case of near-field radiative transfer, $\mathcal{T}$ operator arguments specify that the enhancement of heat flux attainable via nanostructuring can never greatly exceed that of parallel plates, exhibiting resonant surface modes with comparable $\zeta$. For integrated far-field absorption, they have established that structures discovered through topology optimization often achieve near maximal performance.

A selection of our findings for integrated absorption (by Kirchhoff’s law equal to emission after normalizing out the Planck energy of a harmonic oscillator) are shown in Fig.1. In each panel two lines are plotted: $\Phi_{\text{opt}}$, the $\mathcal{T}$ operator bound, and $\Phi_{\text{mat}}$, the application of previous shape independent material limits [9] to angle-integrated absorption. A variety of other examples, including far-field limits for scattering cross sections and near-field limits for radiative enhancement, will be explored in the presentation.

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References

Figure 1: T operator bounds for integrated absorption and thermal emission, adapted from [1]. The first row displays the absorptivity ($\Phi$ normalized by area $A$) bounds $\Phi_{\text{opt}}$ (orange lines) and $\Phi_{\text{mat}}$ (purple lines), for several values of the material figure of merit $\zeta = |\chi|^2/\text{Im} |\chi|$ at a fixed wavelength $\lambda$. These quantities are shown as a function of the wavelength normalized radius $R$ of an enclosing sphere (a), and thickness $h$ of a semi-infinite film (b). Even for small characteristic lengths ($R, h \lesssim 0.1 \lambda$) $\Phi_{\text{opt}}$ is orders of magnitude smaller than $\Phi_{\text{mat}}$. Notably, high absorptivity (super-Planckian characteristics) are still seen for certain subwavelength domains (nanoparticles and thin films). The second row compares this same absorptivity quantity for structures discovered using gradient topology optimization for a variety of metallic (c) and dielectric (d) materials of susceptibility $\chi$, again characterized by $\zeta = |\chi|^2/\text{Im} |\chi|$, to the two $\Phi$ quantities. In panel (c), all structures are bound by a ball of radius $R = 0.05 \lambda$; in panel (d) the confining domain is a ball of $R = 0.5 \lambda$. The inset provides a visualization of the structure (exterior and planar cut) for the rightmost black square. The observation that optimized structures come within factors of unity of $\Phi_{\text{opt}}$ provides case evidence for its tightness.


Discovery of topological metamaterials by symmetry relaxation and smooth topological indicators

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Abstract

Topological metamaterials have emerged, both, to realize and study topological physics, as well as in the search of practical applications. However, systematically designing topological metamaterials has remained a challenge due to the very nature of topology; its robustness. Here we present a novel approach, based on symmetry relaxation and gradient methods that, for the first time, tunes the topological index directly. We have successfully applied the method to design both conventional and higher-order topological systems.

1. Introduction

The birth of topological physics can be dated to the explanation of Quantum Hall Effect by Thouless and co-authors [1] in 1982. In the realm of crystals and periodic metamaterials, the fundamental idea of topology is that one can associate a topological index to a single or a set of dispersion bands below a bandgap. The topological index is integer-valued and it can not change as one smoothly deforms the dispersion bands by changing the material parameters.

The term smooth means that the deformation of the band manifold induced by changing material parameters is continuous and invertible. This requires the band gap to remain open during the deformation. Additionally, the topology is only invariant when the protecting symmetries are respected by the deformation. In summary, for every periodic metamaterial having a unit cell with certain symmetries, there exists a topological index which is protected by these symmetries, i.e. the index can not be altered by smooth deformations which respects the symmetries.

The robustness against defects due to the invariance of the topological index w.r.t. smooth deformations makes topological materials interesting both theoretically as well as practically. This same robustness however, is a challenge from a design point of view, because it does not allow us to identify the direction of growth of the topological index by making infinitesimal perturbations to the material parameters. The systematic design of topological metamaterials (and the systematic discovery of novel topological condensed matter phases) has therefore remained an exploratory research topic, as exemplified by the variety of different approaches (see references in [2]).

In this paper, we introduce a novel approach to design topological metamaterials. In contrast to other approaches, we tune the topological index directly. To do so, we relax the protecting symmetry, thereby lifting the discreteness of the topological index. We call this a smooth topological indicator, which equals the topological invariant when the symmetry is intact and continuously interpolates between different topological phases when the symmetry is broken. This smooth topological indicator is a continuous, (almost everywhere) differential function of its parameters. One can therefore compute the gradient of the topological indicator with respect to the material parameters to identify the direction of its growth. Optimizing the topological indicator will therefore tune a system from its trivial- into a topological phase.

2. Results

We now illustrate the method using a simple topological system: a 1D continuous elastic metamaterial bar, made of a periodically repeating unit cell of length $W$, consisting of a three-material sandwich [4] with constant density $\rho$ and elastic moduli $E_A$, $E_B$ and $E_C$, respectively (Fig. 1a). The rod satisfies the 1D elastic wave equation,

$$
\rho(x) \partial_t \psi(x, t) + \partial_x [E(x) \partial_x \psi(x, t)] = 0,
$$

where $\psi$ is the displacement along the longitudinal direction ($x$) of the bar. The system has multiple bandgaps (Fig. 1b). To each band gap one can associate a (multiband) Berry-phase like [3] topological index. Throughout the design process we fix the densities and widths of the layers as well as $E_A$, while we allow the elastic moduli, $E_B$ and $E_C$, to vary freely, looking for a parameter path that tunes the band gap under consideration from trivial to topological.

The topological index is protected by inversion symmetry which is intact if $E_B = E_C$ and broken otherwise. If inversion symmetry is intact the topological index takes the discrete values of $\theta = 0$ or $\theta = \pi$ in the trivial and topological phase respectively. It further, by its robustness, remains invariant for all values of $E_B = E_C$, and jumps from 0 to $\pi$ if the band gap closes. This is depicted in Fig. 1c for the fifth band gap: on the diagonal line ($E_B = E_C$)
the Berry phase indeed remains invariant until it jumps at around $E_B = E_C = 7.5$ GP, which corresponds to a material configuration for which the fifth band gap closes. If, however, the inversion symmetry is relaxed (away from the diagonal in Fig. 1c) the Berry phase is no longer protected and becomes a continuous function of the material parameter. We can then employ gradients to identify the direction of growth of the Berry phase and optimize the system from trivial to topological (red path Fig. 1c).

For a 1D continuous system as discussed here the topologically non-trivial phase predicts the existence of interface modes (e.g. [4]) with a frequency in the band gap. This interface mode can be observed if a trivial and a topological system are glued together. The composed system with the interface at which the topology switches from trivial to topological is forced at frequencies in the common band gap which will excite the topological interface mode during the optimization process is depicted in Fig. 2. The edge modes are not protected and can be observed to be gapped, while the corner modes are truly topological and therefore gapless.

3. Conclusions

In this summary we have introduced a novel approach to design the topology of a material. The method only requires a parametrization of the model, the relevant topological index and the symmetry which protects the index, no prior knowledge of the model details is needed. The method is applicable to both Berry phase like and symmetry based topological indices as well as to conventional and higher-order topological systems.

References


Integrated lithium-niobate photonics: structures, devices, systems and applications
Spectral engineering of LNOI waveguides: from ultranarrow to broadband

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Abstract
The development of advanced nano-structuring capabilities on LNOI is paving the way towards low-footprint photonic circuits leveraging appealing functionalities of LiNbO3 for ultrafast signal processing and wavelength conversion. In the talk we shall present ultra-narrow bandpass and multi-resonance filters, implemented with phase-shifted Bragg gratings in LNOI photonic wires. We shall also discuss designs of dispersion engineered waveguides for broadband second harmonic generation, appealing for wavelength multicasting, ultrashort pulse frequency doubling and enhanced quadratic cascading in the telecom band.
Periodically poled lithium niobate microdisk resonators on insulator

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Abstract

We developed a fabrication process of periodically poled lithium niobate (PPLN) photonic devices on insulator with the assistance of piezoresponse force microscopy (PFM), providing us the abilities to fabricate microdomain structures down to the scale of several tens of nm. The efficient harmonic generation with $d_{33}$, the largest nonlinear coefficient of LN, utilized in the whole microcavity and high-order harmonic generations were demonstrated in PPLN microcavities with single and double spacial periods, respectively. The work paves the way to achieve efficient frequency conversion in on-chip LN photonic devices.

1. Introduction

Nonlinear optical frequency conversion with second-order susceptibility has significantly potential applications in modern photonics. As a type of nonlinear optical crystal with giant effective nonlinear coefficient, lithium niobate formed into microcavities could be a good platform for efficient frequency conversion, such as harmonic[1, 2, 3, 4, 5], sum-frequency[6], parametric[7] and difference frequency generations and their applications. To fully take advantage of the nonlinear coefficient $d_{33}$ of lithium niobate, periodically poled structure is necessary. In this situation, the mismatch of the modes caused by the material dispersion could be compensated by periodically reversing the axis of the crystal, making momentum conservation of nonlinear frequency conversion process more flexible.

In this paper, we report the fabrication of PPLN microcavities with high quality factors and flexible fine domain structures. The domain patterns with complicated and fine strutures, even down to the scale of 100 nm for a single unit, could be obtained by the method of PFM-assisted polarization. To illustrate the fabrication abilities, radial single-domain PPLN (SPPLN) and dual-PPLN (DPPLN) microdisks for harmonic generations were fabricated. The SHG with the largest nonlinear coefficient $d_{33}$ utilized and the cascaded harmonic generations were obtained in the fabricated SPPLN and DPPLN microdisks, respectively. The characteristics of the microcavities and the conversion efficiency of the corresponding nonlinear processes were investigated as well.

2. Experiments and results

2.1. PPLN microdisks with single period

The radial SPPLN microdisk with a poling period of $\sim 1.98 \mu m$ was fabricated by photolithography, ion beam etching, probe polarization and post-processing (details see Ref. [8]). The harmonic generation experiment was carried out with a narrow band tunable laser in 1550-nm band served as pump. By tuning the wavelength of the pump laser to the resonances of the microdisk, the energy was coupled into the microcavity via a tapered fiber. When the quasi-phase matching (QPM) condition was also satisfied, we could obtain the SHG signal by the grating spectrometer. The normalized SHG conversion efficiency was measured to be 1.44% W$^{-1}$. To further confirm the polarization state of the modes participating in the nonlinear process, the polarization of lateral-scattering light from the resonator was identified. The results indicated that the pump and the signal modes were TM polarization, which means that the largest nonlinear coefficient $d_{33}$ was utilized in the whole microdisk resonator.

2.2. PPLN microdisks with double periods

Figure 1: The PFM images of DPPLN microdevices. (a) The PFM image of a DPPLN microdisk without post-processing, the blue area at the edge of the microdisk has been polarized. (b) Details of the polarized domain of (a) marked by the black box. The minimum width of the polarized unit is estimated to be 100 nm.

For the satisfaction of the QPM of several nonlinear processes simultaneously, such as SHG and cascaded harmonic generations, DPPLN microdisk resonators with more reciprocal wave vectors were fabricated by the same process of SPPLN. The PFM images of the microdisk without post-processing are depicted in Fig. 1. From the details...
of the Fig. 1(b), we can estimate the finest poling domain is about 100 nm, which is a great challenge to fabricate such a fine domain structures by a conventional electrode polarization. The optical microscope image of a 20-µm-radius microdisk and its Q factor were depicted in Fig. 2.

![Optical microscope image of a 20-µm-radius microdisk](image)

Figure 2: The characteristics of a DPPLN microdisk. (a) The optical microscope image of a 20-µm-radius DPPLN microdisk, the dark pink area in the middle of the microdisk represents the silica pillar. (b) The measured Q factor of the DPPLN microdisk resonator. The loaded Q obtained by Lorentz fit is 1.43 × 10^5.

The microdisk was pumped by a single continuous tunable laser in 1550-nm band, and the nonlinear signals were detected by a grating spectrometer. Benefiting from the more reciprocal wave vectors of the DPPLN microdisks, QPM conditions were easy to be satisfied, therefore, we obtained the SHG and the third/fourth harmonic generations (THG, FHG) in the grating spectrometer simultaneously. As is depicted in Fig. 3, the conversion efficiency of the SHG and the THG were measured to be 51% W⁻¹ and 6.8 × 10⁻⁵% W⁻², respectively.

![Nonlinear signals and corresponding efficiencies](image)

Figure 3: The nonlinear signals and the corresponding efficiencies of dual-periodically poled microdisk resonator. (a) The SHG signal and its normalized conversion efficiency (the inset), measured to be 51% W⁻¹ by linear fit. (b) The dependence of the THG power on the pump power, the maximum conversion efficiency was measured to be 6.8 × 10⁻⁵% W⁻².

3. Conclusion

In conclusion, we report the fabrication of PPLN microresonators with the combination of the standard semiconductor fabrication process and the PFM-assisted polarization method. SPPLN and DPPLN microdisks were fabricated, SHG with d₃₃ utilized and more than one nonlinear frequency conversion processes were obtained respectively, benefiting from the multiple reciprocal wave vectors provided by the flexible domain structures. By optimizing the fabrication process, we believe that the Q factors of the PPLN microcavities and the nonlinear conversion efficiencies could be further improved. The work paves the way to achieve nonlinear frequency conversions with high efficiency for modern photonics.

References


Opto-mechanical metasurfaces and metamaterials
Concept of mechanically tunable terahertz circular polarizer

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Abstract

A terahertz circular polarizer that transmits only one handedness of circular polarization is proposed. The circular polarizer is developed based on an extended analytical method incorporating network analysis and the genetic algorithm. Simulations reveal that the design enables a 15-dB extinction ratio relative bandwidth of 14.3%, ranging from 254 to 293 GHz. The center operation frequency can be tuned by design from 220 to 330 GHz through varying the thickness of dielectric spacers. The performance suggests the potential of the structure to function as a mechanically tunable terahertz circular polarizer, provided that air gaps are included in between the dielectric spacers.

1. Introduction

Circular polarizers that selectively transmit one handedness of circular polarization while blocking the other are highly desired in spectroscopy, imaging, and wireless communications. Conventionally, circular polarizers can be realized by employing three-dimensional chiral structures such as helix arrays [1]. However, such structures typically suffer from low extinction ratio and high fabrication complexity.

Instead of non-planar structures, it was shown that planar multilayer structures are a viable alternative for realizing circular polarizers with low profile [2, 3]. However, the demonstrated extinction ratio, efficiency, and bandwidth must be further improved to satisfy practical requirements in the terahertz domain.

Here, a metasurface-based circular polarizer that enables a high extinction ratio and high efficiency is proposed. The proposed design is developed based on an extended analytical method that employs network analysis to calculate the S-parameters of the metasurface. The genetic algorithm is implemented to find the optimal parameters for the three metallic layers to collectively provide an improved extinction ratio over a wide bandwidth. The physical realization involving admittance extraction is subsequently conducted to meet the optimal parameters.

2. Design

Different from the method presented in [2], here we adopt metallic patterns whose equivalent circuits along the x- and y-axes are being predominantly inductive and capacitive, respectively. To simplify the analysis, we assume that the employed metals are lossless. The admittance tensor of the ith metallic layer thus can be expressed as

\[
Y_i = \begin{bmatrix} 1/(j\omega L_i) & 0 \\ 0 & j\omega C_i \end{bmatrix},
\]

where \(L_i\) and \(C_i\) are the equivalent inductance and capacitance, respectively. To introduce the magneto-electric coupling, the ith metallic pattern is rotated by an angle of \(\varphi_i\), which is limited to an integer multiple of 45° to avoid losing pattern connectivity with the neighbouring unit cells. The admittance tensor of each metallic layer then becomes \(Y_i = R_i Y_d R_i^T\), where \(R\) is the rotation matrix [3]. Assuming lossless dielectric spacers, the ABCD matrix is employed to describe the scattering property of the anisotropic metasurface that contains three metallic layers separated by dielectric spacers [2], which yields

\[
\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ nY_{11} & 1 \end{bmatrix} \begin{bmatrix} \cos(kd_1)I_1 & -j\sin(kd_1)\eta_d n \\ j\sin(kd_1)\eta_d^{-1} n & \cos(kd_1)I_1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ nY_{22} & 1 \end{bmatrix} \begin{bmatrix} \cos(kd_2)I_2 & -j\sin(kd_2)\eta_d n \\ j\sin(kd_2)\eta_d^{-1} n & \cos(kd_2)I_2 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ nY_{33} & 1 \end{bmatrix},
\]

where \(k, \eta_d\) are the wavenumber and dielectric spacer wave impedance, respectively. \(d_1\) and \(d_2\) denote the thickness of each dielectric spacer, \(I\) and \(n\) represent the 2×2 identity matrix and 90° rotation matrix, respectively. The S-parameters of the metasurface under linearly polarized incident waves can be written in terms of ABCD matrix as

\[
\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \left( -\begin{bmatrix} n & \eta_0 \\ \eta_0 & n \end{bmatrix} + A \right)^{-1} \begin{bmatrix} 1 & \eta_0 \\ \eta_0 & 1 \end{bmatrix} \begin{bmatrix} \eta_0 & n \\ n & \eta_0 \end{bmatrix} - C \right)^{-1},
\]

where \(\eta_0\) is the wave impedance of free-space. It should be noted that the S-parameters of the metasurface under LCP or RCP incident waves should be transformed from linear basis to circular basis. Once the metasurface transmission coefficients under circularly polarized incident waves are determined, the genetic algorithm is then implemented to find the optimal values of \((L_i, C_i, \varphi_i)\) for each metallic layer, and \((d_1, d_2)\) for dielectric spacers.

The physical realization of each metallic layer is obtained by designing specific patterns with the desired inductive and capacitive responses along the x- and y-axes,
respectively. Admittance extraction of each metallic layer is performed based on simulation results using [2]

\[ Y_s = \left[ \frac{1 - S_{11}}{\eta_1} - \frac{1 + S_{11}}{\eta_2} \right] \left[ I + S_{11} \right]^{-1}, \]  

(4)

where \( \eta_1 \) and \( \eta_2 \) denote the wave impedances of the adjacent media. Hence, the equivalent inductance \( L_i \) and capacitance \( C_i \) of each metallic layer can be readily calculated and matched to the optimized values.

3. Results

As a proof of concept, a circular polarizer that transmits RCP waves but rejects LCP waves is designed based on the extended analytical method. Figure 1 depicts the 3D structure of the unit cell. To reduce the material losses, gold is employed for the metallic layers, and cyclic olefin copolymer (COC) with a relative permittivity of \( \varepsilon_r = 2.33 \) and loss tangent of \( \tan \delta = 0.0005 \) is utilized as dielectric spacers [4]. Figure 2 shows that a simulated 15-dB extinction ratio relative bandwidth of 14.3% from 254 to 293 GHz can be achieved, where the extinction ratio is defined as the transmittance ratio of \( T_{RR} / (T_{LL} + T_{LR} + T_{RL}) \). Moreover, simulation results reveal that the transmission efficiency of RCP waves is above 90% over the entire bandwidth of operation.

Figure 3 illustrates the design flexibility of the circular polarizer. Its center operation frequency can be tuned by design from 220 to 330 GHz through varying the thickness of each dielectric spacer. The performance reveals potential mechanical tunability of the structure, by separating the three metallic layers from each other with air gaps. Moreover, further simulations suggest that by rotating the metallic layers by 90° with respect to the \( z \)-axis, the proposed design can also function as a LCP polarizer.

4. Conclusions

A circular polarizer exhibiting a simulated 15-dB extinction ratio fractional bandwidth of 14.3% from 254 to 293 GHz is proposed. The circular polarizer can filter circular polarization of the preferred handedness with a transmission efficiency beyond 90% over the bandwidth of operation. The proposed design holds the potential of mechanical tunability and can be applied in imaging and spectroscopy.

References

Nanophotonic platforms for light emitting metasurfaces

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Abstract

The development of novel nanoscale light sources has tremendous potential for high-performance applications such as integrated optoelectronic circuits, and for other sensing and medical applications. Novel nanophotonic platforms based on quantum phenomena have recently attracted significant research attention with breakthroughs in light emission from IET (inelastic electron tunneling) based MIM tunnel junctions [1] and, more recently, BIC (bound states in continuum) cavities [2] and PT-symmetric non-Hermitian systems [3]. In this talk we focus on two major research themes (a) Two-dimensional PT (parity-time-reversal) symmetric metamaterials and (b) Improvement of light emission efficiency in electrically driven MIM tunnel junctions. We will briefly discuss our key findings given below -

a. Improving gain in III-V semiconductor nanocylinders [4]; using these results, we propose an active 2D non-Hermitian metamaterial consisting of vertically coupled III-V semiconductor nanoresonators that realizes robust spectral singularities tuned through coupling between PT resonators.

b. Enhanced radiative efficiencies from electrically driven nanostrip metal-insulator-metal tunnel junctions due to efficient coupling between lattice resonance and the fundamental gap plasmon mode [5].

Acknowledgements

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References


Applications of metasurface optics in atom-based sensors

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Abstract
The discrete electronic energy levels in atoms and the ability to probe and control them using their interactions with light fields have enabled a host of applications in quantum sensing and metrology. In this talk, I will describe the realization of quantum sensors in thermal and cooled neutral atoms and illustrate their benefits and challenges via examples of atomic inertial sensors and magnetometers. I will discuss critical developments in nanophotonic engineering that are needed to improve the utility and performance of atomic sensors and our progress towards developing a photonic-integrated atomic magnetometer using metasurface-based polarization optics.

1. Introduction
Atom-based quantum sensing utilizes discrete energy transitions of atomic electrons to measure physical quantities that include time, electromagnetic fields, and inertial motion. Measurements based on this principle can be very precise and accurate, because atomic transitions can have very high frequencies corresponding to high measurement resolution, and the interactions between well-isolated atoms with a particular physical quantity can be strong and stable over time. Finally, atoms of the same element and isotope are truly identical, which suggests that they are ideal as measurement standard. For these reasons, state-of-the-art sensing performances have been observed in controlled laboratory settings. However, it is difficult to achieve similar performances on mobile platforms, largely due to implementation challenges driven by the size and complexity of quantum sensing systems. This field would thus greatly benefit from engineering approaches to miniaturize and simplify sensor designs.

2. Opportunities for nanophotonics in atom-based quantum sensing
In this talk, examples of using neutral atoms for sensitive measurements of magnetic and inertial fields will be described. These include optically-pumped atomic vapor magnetometers [1] and inertially-sensitive atom interferometers [2] (Figure 1), whose operation (e.g., quantum system preparation, manipulation, and detection) and performance rely on interactions between atoms and nearly resonant photons and having precise control over the intensity, direction, and polarization of the interacting light waves. Current atomic sensors consist of discrete, macroscopic electro-optical components that drive system volume and complexity and limit their scalability and performance in dynamic environments.

Meanwhile, recent advances in nanophotonics, most especially in the developments of diffractive and metasurface components [3, 4], provide a powerful set of tools and techniques that can be tailored for integration with atomic systems, thus presenting potential solutions to miniaturize devices and enable more efficient location, addressing, and detection of atoms. Critical chipscale components that will be discussed include metasurface-based beamsplitters and waveplates, diffractive beamshaping optics, and integrated delivery optics.

3. Development of photonic-integrated atomic magnetometer
Finally, I will describe our group’s progress on developing a photonic-integrated atom magnetometer. In an optically-pumped atomic magnetometer, excitation of an atomic transition with a circularly-polarized light orients atomic spins (such as rubidium) along the propagation direction of the excitation (pump) beam. These spins precess in the presence of an orthogonal magnetic field, at a...
frequency proportional to the product of the gyromagnetic ratio and the magnitude of the magnetic field, B. The spin precession causes polarization rotation of a linearly polarized, off-resonant probe beam that is used to infer B. Currently, optical pumping and polarimetry are accomplished through polarization rotation of the pump and probe beams by bulk birefringent waveplates, and detection of the probe beam on a set of balanced detectors after it is split by a polarizing beamsplitter.

Our simplified magnetometer design would replace these discrete, bulk components with metasurface-based polarization optics which can be directly integrated with the vapor cell enclosure. Designs for near-infrared metasurface components (Figure 2), their fabrication progress, along with analysis of their projected sensing performance will be presented.

![Figure 2](image)

Figure 2 (a) Schematic and top-view of the metasurface polarizing beamsplitter design, whose design approach has been adapted from [5]. (b) Far-field projection of the transmission from a 45-degree linearly polarized input beam, showing polarization-dependent separation of the output, with a split angle of ~20 degrees.

References

Plasmonics and nano-optics
Hole Transporting Materials with Strategy of Flexible Core and Tunable Conformation for Efficient and Stable Perovskite Solar Cells

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Perovskite solar cell (PSC) is a promising photovoltaic technology that can provide high efficiency via low-cost solution process. In order to achieve the best performance and make it viable for future photovoltaic technology, in addition to the perovskite active layer, the use of interfacial layers such as hole transporting layer (HTL) are crucial. Although lots of efforts on developing highly efficient hole transporting materials (HTMs) have been conducted during last decade,[1] very few HTMs can satisfy the demand of PSCs, and the commonly used HTMs are still limited in Spiro-OMeTAD, PEDOT:PSS and PTAA for highly efficient PSCs. Considering the limitations of these highly efficient HTMs such as the necessity of doping (for Spiro), high cost (for PTAA) and poor stability (for PEDOT:PSS), developing new HTMs is still urgent for highly efficient and stable PSCs. As reported literatures, HTMs can be mainly classified into two types based on their chemical structure; one is those containing rigid spiro unit as core and another is those containing planar unit as core. However, both types have their own advantages and disadvantages. In general, the former is more efficient to extract holes from perovskite and suppress the bimolecular recombination but mobility is usually low due to the rigid 3D core structure which prevents from formation of intermolecular π-π stacking, while the latter usually has higher mobility but suffers from recombination. Our interest mainly focuses on designing new HTMs to meet the gap between the two classic HTMs via introducing a “flexible core with tunable conformation (FCTC)” strategy. With the flexible core, the HTMs can tune their configurations based on the interactions between side arms and perovskite or interactions between side arms themselves, which may lead to a good balance of mobility and charge recombination. In this talk, I will present three HTMs based on this strategy, employing flexible saddle-shaped cyclooctatetraethiophene or bifluorenylidene as core and triphenylamine units as arms.[2-3] Both cyclooctatetraethiophene and bifluorenylidene more flexible than rigid spiro unit in Spiro-OMeTAD and fit well into our strategy. The influence of the location of arms on the dihedral angles, molecular configuration, packing characteristics and the resultant film morphology will be discussed. In addition to HTMs, the passivation of perovskite with organic molecular materials will be briefly discussed.[4]

References
Metamaterial Absorber-enhanced Light-harvesting and Light-energy conversion

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Abstract
In this talk, we will present an overview of metamaterial absorber-enhanced light-harvestings and their use in the light-energy conversion devices, such as hot electron generation for photochemistry and photothermal for bolometry.

1. Introduction
Broadband or narrowband perfect light absorption has always been one of the longstanding goals for optics and optoelectronics. However, naturally occurring materials used as absorbers have always failed to meet this requirement because of their large impedance mismatch between them and free space. Artificial metamaterial (or metasurface) absorbers (MMAs) have offered us an opportunity to achieve perfect light absorption from optical to microwave regimes because they can create impedance matching to free space with effective electric and magnetic responses.[1]

Typically, an MMA is a sandwiched structure which is composed of a continuous metallic ground layer, a middle dielectric layer, and periodically arranged metallic resonators atop. Many MMA-based applications have been demonstrated in the last decade, such as sensing, photodetection, hot electron generation, imaging, bolometry, thermal emission, solar thermophotovoltaics, mechanical manipulation, photothermal, etc. Firstly, we will discuss design principles of MMAs, such as a way to obtain MMAs with unabated size-independent absorption, and a way to achieve broadband or narrowband absorption. Following that, we will discuss the hot electron generation and photothermal applications of MMAs.

2. Recent progress and main results
2.1. Some design principles for MMAs
The top resonators are important for tailoring bandwidth, resonant wavelength, and maximum absorption of the MMAs. However, their maximum absorption is usually weakened as the size of resonator changes due to the stringent impedance matching conditions. We experimentally demonstrated a design rule to achieve MMA with unabated size-independent absorption—its absorption is robust to resonator’s size change by using a metal square inscribed with a hollow square (MSIHS), as shown in figure 1(a).[2] The maximum absorption of the MMA maintains above 98% as the size of the resonator changes from 600 nm to 1500 nm in the mid-infrared region while the square resonator only demonstrates a maximum absorption when size=800 nm.

Another challenge of the MMA design is achieving broadband absorption due to the intrinsic narrow linewidth of surface plasmon polaritons or localized surface plasmon. Using a space-filling Gosper curve, we design a broadband MMA that has an average absorption of 95.78% from 2.64 to 9.79 μm, leading to a broadband bandwidth of 7.15 μm, as shown in figure 2.[3] The broadband absorption in the mid-infrared region can be used for surface-enhanced infrared spectroscopy and thermal imaging.

Figure 1: (a) Geometry of the MMA structure; (b) Simulated (solid lines) and experimental (dashed lines) absorption of MAs with different values of l (left to right: 800, 900, 1000, 1100, 1200 nm); Simulated absorption spectra of MSIHS (c) and square resonator (d) with l changes from 500 to 1600 nm (Δ=100 nm).
2.2. Hot electron generation for photodetection and photochemistry

Hot electron generated from the Schottky interface between a metal and semiconductor can be used for photodetection and photochemistry.[4] We use a chiral MMA for plasmon-induced polarization-sensitive photochemistry involving hot electrons, with giant differential chiral responses, as shown in figure 3(a).[5] The giant chiral hot electron generation rate originates from the giant optical absorption, as shown in figure 3(b)-(d). This work suggests that the MMA can be used in polarization-sensitive photodetection and photochemistry.

Figure 2: Broadband MMA based on a space-filling Gosper curve. (a) resonator shape of the MMA; (b) cross-section view of the MMA; (c) detailed absorption and bandwidth of stage 3 MMA.

Figure 3: (a) Schematic of the chiral MMA. (b) chiral absorption spectra of the MMA. (c) and (d) chiral hot electron generation rate under left circularly light and right circularly light, respectively.

2.3. Photothermal

A new type of chiral absorber was proposed by combining plasmonics and thermal physics, as shown in figure 4(a).[6] The chiral MMA can achieve differential optical absorption and it converts light into differential heat, leading to a chiral photothermal effect, as the electromagnetic and photothermal map shown in figure 4(b) and (c). It has potential applications in polarization-sensitive surface photochemistry and chiral bolometers.

Figure 4: (a) Schematic of the chiral absorber; (b) Electric field intensity distribution under chiral light illumination; and (c) Temperature profile under chiral light illumination.

3. Conclusions

In conclusion, by reasonable MMAs design, one can achieve perfect narrow and broadband light absorption. Subsequently, one can convert the perfect light absorption into useful signals, such as electron and thermal and thus is promising for photothermal, photochemistry and modern nanophotonics.

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References

Conformal Symmetry and its Application to Plasmon Localization

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Abstract

Transformation optics provides us an elegant and insightful way to harness symmetry. By leveraging the conformal symmetry, we propose a general strategy for the design of light-stopping plasmonic metasurfaces, which is able to localize surface plasmon polaritons in space longer than their plasmon lifetime. Furthermore, by investigating the properties of conformal symmetry, we stress its significance in tuning the band structures of subwavelength plasmonic systems, which can be extended to a variety of applications via different conformal transformations.

1. Introduction

Transformation optics (TO) has been regarded as a specially useful tool for the harnessing of symmetry in electromagnetism. In particular this technique has been implemented to the study of a class of gratings generated by conformal transformation of a metallic slab whose Bloch eigenmodes are dictated by its translational symmetry [1]. Under quasistatic limit, eigenfrequencies at $\Gamma$ point of the Brillouin zone (BZ) are protected by conformal transformation, whereas at the rest of reciprocal space, this symmetry is broken. It is obvious that conformal symmetry, by taking advantages of the link between the virtual and physical space, allows us to tune the band structures of a plasmonic system.

On the other hand, slowing light has been a fundamental breakthrough in optics. In order to obtain a light-stopping plasmonic system which can localize plasmons longer than their lifetime at targeted frequency range, complicated and time-consuming design is always inevitable. Thus, an insightful strategy for realization of flat bands is a challenge worth pursuing.

In this work we further investigate the properties of conformal symmetry, and leverage it as a guide for the design of plasmonic metasurfaces with extremely flat bands, enabling the localization of SPPs over timescales, whilst focusing the field at the hot-spot of grating with minimizing radiative losses[2].

2. Results and discussion

The Laplace equation $\nabla^2 \Phi = 0$, which governs the subwavelength dynamics of SPPs under quasistatic limit is symmetric under a conformal coordinate transformation. Consider the system shown in Fig. 1(a); a series of gratings in the physical $x - y$ frame can be mathematically generated from a single slab positioned at $u = u_0$, in the virtual $u - v$ plane, with constant thickness $d$, via the following conformal transformation:

$$z = \frac{\Gamma \ln \left[ \frac{1}{e^{i\nu} - \nu_0} + i\nu_0 \right]}{1}$$

with $z = x + iy$, and $w = u + iv$. The scaling factor $\Gamma$ determines the period $a = 2\pi \Gamma$ of the gratings, and $w_0$ is the modulation depth parameter [1]. Here, we choose $\nu_0 = w_0/\left[ e^{2(\nu_0 d)} - w_0^2 \right]$ which ensures that the flatness of the second surface at $u = u_0 + d$. In our calculations, Drude model is considered in our metasurfaces, with plasma frequency $2$ eV. The electron scattering rate is chosen to $\gamma_e = 2$ meV, which helps us to visualize the eigenmodes of the plasmonic system. The optical response is obtained via semi-analytical solutions calculated by solving the full set of Maxwell’s equations via transformation optics, and finding the poles of scattering matrix[3].

Figure 1(b) shows the band structures of the grating with both weak ($w_0 = 1.0$) and strong ($w_0 = 2.5$) modulation depth. The dotted black line represents the band-folding of a the slab with thickness 7.5 nm. At the BZ center, the eigenmodes for considered class of gratings are fixed, which are solely decided by the analytic dispersion of the slab in the virtual frame, which can be written as $e^{i[k_i d]} = \pm i\frac{a}{\gamma_{e}}$, whilst at the BZ edge, gaps open whose extent increases as the modulation-depth parameter $w_0$ ranging from 0 to $e^{w_0}$, where the transformation will feature the singularity[1]. This process allows us to tune the bands at targeted frequency, and extremely flat bands can be obtained with strong modulation depth, indicating such conformal symmetry assisted plasmonic system a powerful candidate for plasmon localization.

Figure 1(b) also allows us to investigate two key features of conformal symmetry at $\Gamma$ point: first of all, the eigenfrequencies of the metasurfaces generated from the same virtual space are invariant; furthermore, degeneracy at $\Gamma$ point can be obtained. It is worth mentioning that this degeneracy cannot be predicted by geometrical considerations based on conventional point group theory in the physical space, since gratings here only possess $C_{1h}$ symmetry. It is the conformal symmetry that eliminates the band gap at the zone center and sustains the degeneracy for a whole class of gratings, which can be further visualized from the
Figure 1: (a) Schematic illustration of the proposed conformal plasmonic metasurfaces with different modulation depths in the physical $x-y$ frame generated from a thin metallic slab in the virtual $u-v$ frame via conformal transformation. (b) Plasmonic dispersions calculated for gratings with $w_0 = 1.0$, $w_0 = 2.5$ are shown as blue and red markers. The dotted line shows the dispersion of a slab folded into the first Brillouin zone. The dashed yellow line corresponds to the light line. (c)-(d) Electric field distribution induced on gratings with $w_0 = 2.5$ and $w_0 = 1.0$ under dipole excitation at each band edge frequency $E_1$ and $E_2$ marked in (b).

Figures 1(c) and (d) show the electric field distributions of the two gratings under dipole excitation. Here, the electric dipole oriented along $y$ axis is placed 100 nm above the grating, and its frequency is chosen at the band edge frequency of each grating. It is clear that for grating with larger modulation depth, highly localized field profile is obtained, while for weak grating, the field is almost delocalized. In addition, large field enhancement can be achieved in strong grating case, which demonstrates another merit of our class of light-stopping system. Detailed discussion on the performance of conformal symmetry assisted light-stopping system will be presented in the full paper.

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References


Electron energy-loss spectroscopy of hybrid silicon-on-gold nanoresonators

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Abstract

Using electron energy-loss spectroscopy (EELS), we show that high-refractive-index silicon nanoparticles on top of a thin gold layer give rise to low-loss hybrid resonances and strong plasmon launching. We characterize the surface plasmon (SP) modes which are launched by the spherical silicon nanoparticle in the presence of the thin gold layer and the Mie modes of the nanoparticle.

1. Introduction

The ability to control light at the nanoscale is of paramount importance for optical and electronic circuits. Dielectric and high-refractive-index semiconductor nanoresonators have low losses, as well as magnetic and electric responses in the visible spectrum \cite{1}, however, they typically have moderate confinements which are on the order of the wavelength – scale. As an alternative, metals support subwavelength plasmons but have high losses and no significant magnetic response \cite{2, 3}. A promising solution is hybrid silicon-metal nanoresonators, which combine the ability to confine light at nanoscale due to the presence of SP resonances at the metal interface with low losses of high-refractive-index semiconductors \cite{4, 5}.

In this work, we demonstrate how the SP modes are launched by a spherical silicon nanoparticle located on top of a thin metal layer. The silicon-on-gold nanoresonators (Fig. 1.) give rise to the hybrid modes, which show that the silicon nanoparticle is an efficient SP launcher. Moreover, it will be shown that silicon nanoparticle can act as a SP reflector when the SP is launched in the metal film close to the nanoparticle. The nanoparticle Mie modes in presence and strong plasmon launching. We characterize the surface plasmon dispersion curve for silicon / gold / silicon nitride stack with overlayed zeros of the spherical Bessel function \cite{6}.

2. Results

Figure 1 (b) and (c) shows the typical experimental spectra for the spherical silicon nanoparticle on a silicon nitride layer and on a gold / silicon nitride stack. The experiment is performed using GATAN scanning transmission electron microscope (STEM) in the monochromated EELS regime at an accelerating voltage of 300 kV. First, looking at the range above 1.5 eV, it can be seen than there is no significant difference between the Mie modes of the silicon nanoparticle without and with the gold layer when they are excited by an electron beam. The 4 Mie modes of interest here are the magnetic (M) or electric (E) dipole (D) or quadrupole (Q) which can be obtained by a multipolar expansion of the electric field induced by a passing electron near a sphere \cite{6}.

The ED and MQ are located close to each other in energies, but it is possible to differentiate between these two modes using their near field distributions. It can be clearly observed in (b) that when the electron beam moves outside the nanoparticle, the second Mie peak shifts from 2.28 to 2.17 eV. This corresponds to the MQ and ED mode energies. (c) to (h) shows the maps of the 4 first Mie modes for the silicon nanoparticle on nitride. The ED resonance depicts donut like structure with a clear minimum in the middle. The MD resonance is spread over the whole area of the nanoparticle with no clear minimum or maximum. The MQ and EQ have a maximum in the middle with EQ resonance having stronger localization in the center.

Figure 1 (c) also shows the SP resonances. First, there is a SP mode excited by the particle (PP) when the spectrum is integrated over the particle area. When the electron beam moves outside the particle there are new effects appearing: the SP mode of the film (pink line) (FP) and the reflection of this plasmon by the silicon nanoparticle (brown line) (RP).

Figure 2 (b) shows the dependence of the SP energy induced by the particle on the particle size. Here, the PP mode can be defined as the SP of the stack quantized by the first zero of the spherical Bessel function \( j_{01} \) in analogy to Ref. \cite{5}. Figure 2 (a) shows the surface plasmon dispersion curve for silicon / gold / silicon nitride stack with overlayed zeros of the spherical Bessel function for 100 nm radius particle. The intersection of the Bessel function with the SP dispersion curve predicts the SP energies excited by the particle. As expected, when the radius of the nanoparticle is increased, the SP shifts along its dispersion line to the lower energies. However, it should be noted that the SP curve will be slightly modified as well due to the required change in
Figure 1: (a) A STEM image of the nanoparticle with color regions for the experimental spectra on the right. The region colors correspond to the spectra depicted with a corresponding color line. (b) Experimental EEL spectra for a particle on top of 30 nm silicon nitride with \( r = 95 \) nm integrated over different areas. (c) Experimental EEL spectra for a particle on the 10 nm gold / 30 nm silicon nitride stack with \( r = 100 \) nm integrated over different areas. (d) A STEM image of the nanoparticle with color regions for the experimental spectra on the left. (e) - (h) Experimental EEL maps for (b).

The slight difference between the experiment and the simulation can be explained by the deviations in the thicknesses of the thin layers, however, both experiment and simulation follows a similar trend. The SP dispersion is obtained using the dispersion relation from Ref. [7].

The simulation in (b) is performed using finite element method (FEM) solver COMSOL. Multiphysics calculating the induced field by the electron and obtaining the energy loss from it [6]. The experimental points are obtained using GATAN scanning transmission electron microscope (STEM) in the monochromated EELS regime. Both simulation and experiment are performed for the accelerating voltage of 300 kV.

The plasmon reflection can be understood as an interaction of the initial plasmon of the metal film with its reflection. Assuming plane surface plasmon polariton (SPP) waves, the electric field at a position \( z \) from the particle can be written as:

\[
E = E_0 e^{ik_{\text{spp}}z} + r E_0 e^{-ik_{\text{spp}}z} \tag{1}
\]

Assuming that the reflection results only into the phase change \( r = e^{i\phi} \), it is possible to find the resulting SPP wavevector at the position \( L \):

\[
k_{\text{spp}} = \frac{2\pi n + \phi + \pi}{2L} \tag{2}
\]

where \( n \in \mathbb{Z} \). As can be expected, when the distance from the nanoparticle is increased, the energy of the mode is shifted to the lower range and this can be observed in the experimental spectrum (Figure 1 (c)).

3. Conclusions

We have demonstrated the excitation of the SP modes by a spherical silicon nanoparticle and showed how they can be effectively modified by the particle size change. We showed that the silicon nanoparticle can act as a reflector of the SP. The Mie modes were mapped and it was shown that there is no significant modification of them when they are excited by the electron beam.
References


Enhanced circular polarization discriminative photoresponse in the metamaterial integrated anisotropic active materials

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Abstract
Circular polarization discrimination is desired for use in many optoelectronic applications. Nevertheless, the circular polarization extinction ratio (CPER) for absorption of the active materials, typically below 2.5. Based on double polarization selection mechanism, the integration of an asymmetric metamaterial with an anisotropic material can drastically enhance CPER by 6 to 10 times and enhance photoresponse of active materials.

1. Introduction
Circularly polarized light has promising applications in optical communication, imaging, sensing and quantum information processing [1-2]. To promote the advancement of CPL related technologies, the development of compact optoelectronic devices, that can distinguish the chirality, or spin state of CPL, is a central task. Recent advances in nanotechnology have allowed for artificial subwavelength asymmetric structures, providing a new way to enhance photon spin discriminative optoelectronics. However, in an asymmetric metamaterial integrated optoelectronic device, the CPER for the absorption of the optoelectronic material is below 2.5 [3-4]. In this work, we reveal that the integration of an anisotropic optoelectronic material and an asymmetric metamaterial can enhance the CPER by 6 to 10 times. The significant improvement is attributable to a double polarization selection mechanism. We applied our asymmetric metamaterial approach to two well-known anisotropic infrared photodetection materials, i.e. GaAs/AlGaAs quantum wells (QWs) and InAsSb nanowire arrays.

2. Results and Discussion
Fig. 1 (a) or (b) presents a typical combination of an asymmetric metamaterial and an anisotropic (or isotropic) medium. The anisotropic active material can be regarded as a uniaxial medium with a diagonal dielectric constant tensor: \( \mathbf{\varepsilon} = \text{diag}(\varepsilon_3, \varepsilon_3, \varepsilon_3) \). The relative permittivity of the isotropic active medium is \( \varepsilon_3 \). \( \varepsilon_3 \) and \( \varepsilon_0 \) is plotted in Fig. 1 (c). The circular polarization-dependent absorbance spectra of the two composite structures with the anisotropic and isotropic media are presented in Fig. 1(d) and (e), respectively. The circular polarization selectivity provided by the asymmetric metamaterial could be analyzed by the interference between the polarization unconverted field and the polarization converted field in the reflection. For LCP, the interference is destructive in the reflection, so the incident light is efficiently converted into a coupled surface plasmon polariton (SPP) waves, supported by the air-Au-dielectric multilayered system and guided along the twisted metal strips. However, for RCP the interference is constructive, so the incident light is mostly reflected and the coupled SPP wave is not efficiently excited. This discrimination between LCP and RCP is significantly enlarged by the cavity between the layer of strips and the bottom metal plane due to multiple reflection interference. The most interesting point is that the integration of the anisotropic medium with the asymmetric metamaterial provides a much higher CPER than the integration of the isotropic one with the metamaterial (Fig. 1 (f)). The former gives a CPER of around 20, while the latter gives a value of around 2.8, which is consistent with previous reported values for the isotropic medium. The enhancement of CPER is due to the alignment between the primary absorption direction of the anisotropic medium and the polarization of the photonic mode excited by the circularly polarized light with the selected handedness. It is also due to the low or even zero absorption rate of the anisotropic medium in other directions, which limits the absorption of light with the opposite handedness. In this way, the combination of an asymmetric metamaterial with an anisotropic optoelectronic material provides a new way to achieve a high CPER for the absorption of the optoelectronic material.

It is well known that anisotropic optoelectronic materials are easy to find, especially for man-made quantum structures. We applied our asymmetric metamaterial approach to two well-known anisotropic infrared photodetection materials, i.e. GaAs/AlGaAs quantum wells (QWs) and InAsSb nanowire arrays. The asymmetric metamaterial integrated QWs exhibit a CPER of 14 (nearly 11 times higher than that of the same integrated HgCdTe (isotropic)) in the long wave infrared region (Fig. 1 (g), (h), (k)). The asymmetric metamaterial integrated InAsSb nanowire array exhibits a CPER of 12.6 (7 times higher...
than that of the same integrated InAsSb film (isotropic)) in the mid-infrared region (Fig. 1 (i), (j), (l)).

3. Conclusions

For the circular-polarization-discriminative light-matter interaction, we revealed that the integration of an asymmetric metamaterial with an anisotropic optoelectronic material, instead of an isotropic one, can drastically enhance the CPER by 6 to 10 times owing to the double polarization selection mechanism. The alignment between the primary absorptive direction of the anisotropic medium and the polarization of the photonic mode excited by CPL with the selected handedness ensures a prominent absorption rate for CPL.

Figure 1. (a) and (b) Sketches of an asymmetric metamaterial integrated anisotropic medium and an asymmetric metamaterial-integrated isotropic medium for circular-polarization-discriminative absorption. The dimensions are the same in both cases: \( P_x = 1490 \text{ nm}, \ P_y = 1200 \text{ nm}, \ W_x = 300 \text{ nm}, \ W_y = 200 \text{ nm}, \ L = 976 \text{ nm}, \ h = 380 \text{ nm} \). The thickness of the top metal piece is 50 nm. (c) The relative permittivity of the anisotropic and isotropic media. The black solid and dashed lines are with respect to the right axis. The red solid and dashed lines are with respect to the left axis. The red solid line and dashed line are with respect to the right axis. (d) and (e) Absorptance spectra of the anisotropic and isotropic media in the composite structures, as shown in (a) and (b), respectively, under LCP (red) and RCP (blue) light illumination. (f) CPERs for the absorption of the active materials in the composite structures with the anisotropic medium (magenta) and the isotropic medium (green). (g-i) Sketch of the asymmetric composite structure with QWs, HgCdTe, encapsulated InAsSb nanowire array, and the InAsSb film, respectively. (k) CPERs for the asymmetric composite structure with the QWs (magenta) and with HgCdTe (green). (l) CPERs for the asymmetric composite structure with the encapsulated InAsSb nanowire array (magenta) and for that with the InAsSb film (green).

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References

Electron kinetics in epsilon-near-zero optical nonlinearity

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Abstract
The physical mechanisms of epsilon-near-zero (ENZ) optical nonlinearity are modeled and the Drude model is extended to intraband transition induced optical nonlinearity by adopting the statistical parameters. The electron overall effective mass and overall scattering time are proposed, which takes into account the distribution of energy dependent electrons in the nonparabolic band.

1. Introduction
Epsilon-near-zero (ENZ) optical nonlinearity attracts wide interest in optoelectronics and plasmonic photonics for its unique light-matter interaction mechanism.[1, 2] As a transparent conductive oxide (TCO), indium tin oxide (ITO) shows good optoelectronic performance and large ENZ optical nonlinearity.[3, 4] The ENZ wavelength of ITO is usually in near infrared (NIR) wavelengths, and the optical properties in NIR wavelengths are well described by the Drude model.

The physical origin for the ENZ optical nonlinearity is changes in electron properties. To describe the optical nonlinearity accurately and completely, the basis is modeling the Drude parameters plasma frequency (ωp) and the damping factor (γ) with the electron parameters such as effective mass (m*), electron scattering time (τ), Fermi level (EF). The band structure theory is applied to accurately describe the electron properties in optical nonlinear process, and the electrons in conduction band are important because they determines the optical properties in NIR wavelengths. The E – k relation of the conduction band of ITO is nonparabolic, and the electrons have a Fermi-Dirac type distribution in conduction band. Thus the electron parameters used in Drude model should be statistical values taking into account the electron distribution in nonparabolic conduction band.

In this paper, we build the statistical models of electron overall effective mass and electron overall scattering time, which take into account the electron distribution in nonparabolic conduction band. The spectrally-resolved optical nonlinear refractive index could be calculated by the Drude model.

2. Results and Discussion
In first-order approximation, the E – k relation of the conduction band of ITO (fig. 1) is

where ħ is the reduced Planck constant, k is the electron wave vector, m* is the electron effective mass at the conduction band minimum, E is the electron energy referenced to the conduction band minimum, and C is the first-order nonparabolicity factor.

![Figure 1: Schematic diagram of electron distribution in conduction band for no pump (left) and pumped (right).](image-url)

The electron density is

where f0 is the Fermi-Dirac distribution function.
\[ f_0 = \frac{1}{\exp((E - E_F)/(k_B T_e)) + 1}, \]  

(3)

where \( E_F \) is the Fermi level, \( T_e \) is the electron temperature, and \( k_B \) is the Boltzmann constant.

In a nonparabolic band, the electron have an energy dependent density-of-states effective mass

\[ m^*_0 = m^*_0 (1 + 2CE), \]  

(4)

and the overall effective mass should be a statistical averaged value which take into account the electron distribution in the nonparabolic band[3]

\[ \frac{1}{m^3} = \frac{1}{2\pi^2 m^*_0 N} \left( \frac{2m^*_0}{\hbar^2} \right)^{3/2} \int_0^\infty (E + CE^2)^{1/2} f_0 dE. \]  

(5)

The ionized impurity scattering is the dominant scattering mechanism in electron transport of indium tin oxide. The electron energy dependent scattering time is[5]

\[ \frac{1}{\tau(E)} = \frac{N_iz^2e^4}{16\pi^2m^*_0 \hbar^2} (E + CE^2)^{-3/2}(1 + 2CE), \]  

(6)

where \( Z \) is the charge of the impurity, \( N_i \) is the ionized impurity density, and \( \epsilon \) is the static permittivity.

Similarly, the electron overall scattering time statistically averages the energy dependent scattering time over the nonparabolic conduction band by the integration form

\[ \frac{1}{\tau} = \frac{N_iz^2e^4}{32\pi^2m^*_0 \hbar^2} \left( \frac{2m^*_0}{\hbar^2} \right)^{3/2} \int_0^\infty (E + CE^2)^{-1}(1 + 2CE)f_0 dE. \]  

(7)

Thus the Drude parameters \( \omega_p \) and \( \gamma \) could be further calculated by

\[ \omega_p^2 = \frac{N_iz^2e^4}{\epsilon_0m^*_0 \gamma} = \frac{1}{\tau}, \]  

(8)

and the spectrally-resolved optical nonlinearity could be calculated by the Drude model

\[ \epsilon_r = \epsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}. \]  

(9)

3. Conclusions

The physical origin of the epsilon-near-zero optical nonlinearity is changes in electron overall effective mass and overall scattering time, which is caused by intraband transition induced electron redistribution. The optical nonlinear refractive index could be calculated by the Drude model using the overall effective mass and overall scattering time.

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Simulation of plasmon enhanced electric field and its impact on vibrational spectra

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Abstract

Raman and infrared (IR) spectroscopy allow for an unambiguous identification of microscopic objects. Surface-Enhanced Spectroscopies, including SERS improves its cross section by a coupling with plasmon excitations. However, the interpretation of resulting spectra is challenging. This works focuses on the enhancement of the local electromagnetic field associated with metallic nanodisks plasmon excitation. Simulation are obtained by Discrete Dipole Approximation (DDA). This local response is then combined with Time Dependent Density Functional Theory (TD-DFT) to investigate its effect on the vibrational spectrum of hydrogen cyanide (HCN).

1. Introduction

A primordial element in Surface-Enhanced Raman Spectroscopy (SERS) concerns the position of the electromagnetic hotspots and the role of the intensity and inhomogeneity of the local electromagnetic field [1]. The configuration of a molecule in such hotspot will have a major influence on the shape of the final vibrational spectra.

2. Goal

This work aims to investigate the detailed electromagnetic effect (intensity and inhomogeneity of the local field) on the vibrational response.

3. Results

Within DDA, we investigate the electromagnetic response of two coupled metallic nanodisks (Au and Na). The local field enhanced resulting of the excitation of plasmon excitations is then confronted with the extinction spectra of the system to identify bright modes (visible on this spectra) and dark modes (non-visible on this spectra). Figure 1 is an example of a bright mode for two disks of Na (10 nm of diameter) represented by streamlines. This local field is then used in a TD-DFT simulation with the Gaussian package on a small molecule, HCN, to identify its effect on HCN vibrational spectrum depending on the molecule position in the field.

Figure 1: Streamline representation of the enhanced electric field around two nano-disks of metallic sodium at plasmonic resonance (1.3 eV). Color mapping represent E/E₀.

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References

Casimir induced instabilities at metallic surfaces and interfaces

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Abstract

Surface plasmons subject to a surface distortion split asymmetrically in energy resulting in a net lowering of zero-point energy. This is because surface plasmon eigenvalues are the square of frequencies, a statement generally true for electromagnetic excitations. We utilize the method based on conformal mapping to demonstrate asymmetric splitting under surface corrugations leading to a decrease in zero-point energy of a single corrugated metallic surface contributing to surface reconstructions but too small on its own to drive the reconstruction. However, by introducing a second metallic surface more significant lowering of energy is seen sufficient to drive the instability of a mercury thin film.

1. Introduction

Casimir forces arise from zero-point quantum fluctuations of the electromagnetic field and play a central role in biology, adhesion, friction, wetting and a host of other phenomena. Here we are concerned with the impact of Casimir forces on the stability of surfaces in the presence of distortions of various kinds. We are particularly interested in the role of surface plasmons. The generally true fact that the equation of motion of plasmons is second order in time renders to asymmetric splitting of plasmonic modes as a consequence of taking a square root when two plasmonic modes interact. Therefore, there is a net lowering of energy by summing up the frequencies of these two hybrid modes, and thus acts as Casimir bonding mechanism. Such mechanism distinguishes itself from electronic cases due to the fact that electronic equation of motion is first order in time, which implies symmetric mode splits. The above argument applies to any splitting of electromagnetic levels and accounts for the almost universal attractive nature of dispersion forces. With this argument in mind, it is to be expected that when a surface is distorted the ensuing splitting of electromagnetic levels will favor the distortion and the ensuing instability. Of course, other often more powerful forces may oppose the distortion but as we shall show the Casimir instability sometimes wins.

2. Results

We employ a method based on transformation optics in its conformal mapping realization to calculate the scattering matrix of corrugated surfaces and investigate the role of asymmetric splits in the Casimir energy. We then demonstrate that the splitting of plasmonic modes under corrugation indeed decreases surface energy of a single surface. To make such effects experimentally observable, we introduce a second surface, and demonstrate that the asymmetric split can cause the decrease of Casimir energy for the gold cavity system and create instabilities in a mercury thin film.

Figure 1: Flowchart of our numerical method. The left (right) panel shows the metasurface (slab) frame, and the coordinate transformation is given in the text.

2.1. Numerical method

We start from a single corrugated surface with its profile given by the following conformal mapping that transforms a flat surface in the slab frame (see Fig. 1) with the air/metal boundary at \( u=u_0 \) to a corrugated surface

\[
z = \Gamma \ln \frac{1}{e^{z - i w_0}},
\]

where \( w = u_0 + iv \) and \( z = x + iy \) are the surface coordinates in the slab and metasurface frame, respectively. The parameter \( \Gamma \) determines the corrugation period \( a = 2\pi \Gamma \), and the modulation strength \( \Lambda \) is proportional to \( w_0 \). When \( w_0 \) is small, the profile of the corrugated surface is a sinusoidal
function with $A=\Gamma w_0/\exp(u_0)$. The conformal mapping method allows us to match the boundary conditions of fields in the slab frame instead of the metasurface frame. Because the surface in the slab frame is flat, the boundary condition matching becomes straightforward, making the method efficient [1].

2.2. Asymmetric splits of plasmonic modes

![Figure 2: (a) Surface plasmon dispersions of the corrugated and flat gold surfaces are shown by filled dots and cyan surfaces, respectively. (b) The plasmon frequency of corrugated surfaces with respect to flat ones for the lower (red) and upper (blue) bands as a function of $k_y$ at $k_z=0.0$ and $0.5$ are shown by filled circles and open squares, respectively. The geometric parameters are $\Gamma=2.5$ nm, $w_0=0.5$, and $u_0=0$. We use a Drude model with $\omega_p=9$ eV and $\gamma=1e-7$ meV.](image)

Figure 2 shows the asymmetric splits of plasmonic modes under corrugations. The modes are calculated by finding the zeros of $\det(\mathbf{R})'$ in the real frequency axis for a given wavevector, where $\mathbf{R}$ is the reflection matrix of corrugated surfaces in the Fourier basis.

2.3. Plasmonic contributions to reconstructed gold surfaces

It is known that low-index gold surfaces reconstruct to rather complex surface unit cells, and in order to investigate whether the asymmetric splits of plasmonic modes play a role in the reconstruction. We thus calculate such plasmonic mode contributions to the zero-point energy and find that the change converges to -0.2 meV/Å² when the momentum cutoff is still within a continuum model. This confirms that the splitting of plasmonic modes under geometric corrugations decreases the zero-point energy [2].

2.4. Instabilities of the metallic cavity and film

The above decrease in zero-point energy is small compared with surface energy, but such decrease becomes experimentally observable if we introduce a second surface to form a metallic cavity or film. We show the asymmetric splitting of plasmonic modes will cause instabilities of the metallic cavities and films [2].

3. Discussion and Conclusions

We demonstrated that surface corrugations induce plasmonic modes of metal surfaces to split unevenly because the equation of motion of plasmons is second order in time which is generally true for electromagnetic excitations. Such an asymmetric split always decreases the zero-point energy of a single air/metal interface and can give rises to the decrease of the Casimir energy for a cavity system consisting of two metallic surfaces. It also contributes to the instability of a mercury thin film against corrugation. Since such an asymmetric mode splitting is intrinsic to the coupling of plasmonic modes, their contributions can be observed in other hybridized plasmonic systems, leading to one kind of electromagnetic bonding, and can cause the attraction of neutral metallic objects. Last but not least, accurate calculations of zero-point and Casimir energies of complex interfaces usually require a formidable amount of computer resources, and our calculations are made tractable by the conformal mapping technique which can provide an excellent platform to investigate other electromagnetic fluctuation-type problems.

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References

Anapole-assisted Dark Plasmon Excitation in Hollow Silicon Disk

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Abstract
The anapole mode excited by silicon nanodisk provides a mildly enhanced and low loss field while exhibiting non-radiating property. Due to the special nature of anapole mode, much research has focused on the light-matter interaction engineered by the anapole-assisted enhanced field. Here, based on the anapole mode in hollow silicon disk, we proposed a new method for exciting dark plasmon mode.

1. Introduction
Metal nanostructures provide supreme performance in tight confinement of light to nanoscale dimensions by exciting localized surface plasmon resonance (LSPR) [1]. Unlike the bright mode that is directly excited by linearly polarized light, dark plasmon mode [2] typically requires special illumination schemes to excite, such as spatially inhomogeneous fields, non-normal incidence and focused polarization tailored light. On the other hand, the diverse Mie resonators in high-index dielectric nanostructures cannot only compress the electromagnetic fields to the nanoscale, but also produced many attractive effects by engineering the coupling between different resonances sustained in one dielectric nanostructure [3]. For example, the non-radiating anapole, regarded as a kind of dark mode, is produced by destructive interference of electric dipole and toroidal dipole [4]. Own to its nontrivial non-radiating anti-resonance feature, the anapole mode provides minimum far-field scattering and maximum near-field intensity inside the dielectric. In the regime of optical wavelengths, due to the low loss enhanced field generated by the anapole mode of the dielectric nanodisk, it has been widely applied in local field enhancement [5], nonlinear optical effects [6] and Raman scattering enhancement [7]. Nevertheless, the conventional anapole can only offer a relatively mild field enhancement [5,7].

In this paper, we demonstrate that a dark mode in a side-by-side gold (Au) nanostrip dimer can be excited by anapole mode of a slotted silicon nanodisk meanwhile obtaining a considerable enhancement field between the side gap of two Au nanostrips [8].

2. Results and discussions
The electromagnetic properties of the silicon disk were calculated using a 3D finite-difference time-domain (FDTD) method with commercial software Lumerical. The electric field intensity will be tremendously enhanced at anapole mode due to the narrow slit. However, embedding the gold nanostrip dimer into the silicon disk will disturb the original displacement current and change contribution of each multipole, especially the contribution of electric dipole, as shown in Figure 1. Two dark modes (m1, m2) generated by the coupling between anapole and plasmon modes.

Figure 1: The Cartesian multipole decomposition of the scattering spectra for the hybrid structure shown in the insert.

3. Conclusions
The metal-dielectric nanostructure is considered to investigate the coupling effect of anapole mode and
plasmon mode. The simulation results show that the dark mode in a side-by-side Au nanostrip dimer can be excited by the anapole mode of the slotted silicon nanodisk. The anapole-assisted dark plasmon excitation provides a new method for exciting dark mode without special light field illumination.

Acknowledgements

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References

Fluorescent Multi-layered Films for Label-Free Detection of Volatile Organic Compounds

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Abstract

The detection of vapors is fundamental in many different applications, such as air pollution analysis, industrial process monitoring and breath analysis. This work utilizes a styrene copolymer with fluorescent molecular rotors exhibiting aggregation-induced emission as a promising vapor sensor. Capping thin films of such copolymers with different polymers provides a quick and selective means of detecting volatile organic compounds through fluorescence quenching.

1. Introduction

Exposure to volatile organic compounds is known to cause health complications,[1] thus, their detection is important, whether in industrial or urban settings.[2] However, current widely employed quantitative analysis is cumbersome[3-5] and so, simple and fast sensors are needed for environmental and industrial monitoring. Here we propose a sensing system based on fluorescent thin films for that purpose. Optical vapor sensors based on thin-film fluorescent polymers are widely studied[6-9] due to their fast responses, portability and sensitivity.[10] However, fluorescent materials usable in films are limited due to the common occurrence of aggregation-induced quenching.[11,12] In these regards, the discovery of the ground-breaking aggregation induced emission (AIE) fluorophores have opened the door for many solid-state applications.[13,14] Instead of providing a preferred pathway for non-radiative decay, aggregation in the case of AIE restricts fluorophore intramolecular motions (RIM), inducing luminescence from aggregates and in the solid states.[15] Borelli et al have demonstrated the synthesis of styrene copolymers with 2-[4-vinyl(1,1’-biphenyl)-4’-yl]-cyano vinyljulolidine (JCBF) and its potential use for sensing volatile organic compounds.[16] Thin films of such copolymer respond quickly to exposure to organic vapors, which are absorbed by the polymer matrix, causing swelling and local viscosity decrease. This changes the excited state of the JCBF to the radiationless twisted intramolecular charge transfer state and quenches the luminescence. This system is promising due to its fast response as well as the linear relationship between the concentration of vapor analytes and the fluorescence variation. However, multiple vapors induce quite similar fluorescence variation kinetics and magnitudes, hindering selectivity. In this work we investigate the effect of coats of different polymers on JCBF copolymer thin films as an additional selective mechanism. Samples of bare fluorescent copolymer and of the same copolymer capped with different thin film are then exposed to a series of pure analytes. The change in the copolymer emission is measured along exposure time. As a proof of principle, we report the data retrieved capping the responsive emitter with a thin film of polyvinyl alcohol (PVA).

2. Materials and Methods

Styrene copolymers of P(STY-co-JCBF) with 0.08 wt% of JCBF were used.[16] Films were made by spin coating of 8mg/mL solution of the polymer in chloroform on plasma-treated thin glass substrates at 20 RPS for 22 s. Capping layers were spun-cast from PVA solutions in a mixture of water (75%) and ethanol with concentration 30 mg/mL at 175 RPS. The samples were then inserted in a cuvette connected to a vial containing 0.3 mL of analyte solution. Four analytes were tested: Chloroform, Dichloromethane, Toluene and m-Xylene. The emission spectra of the samples were then collected through a fiber-based set-up with an Avantes 2048 spectrometer and excitation wavelength λ=409 nm CW laser.

3. Results and Discussion

The effect of the exposure to volatile organic compounds of the fabricated samples can be seen in Figure 1. The figure shows the normalized intensity of the fluorescence maximum as a function of exposure time to chloroform (black), dichloromethane (red), toluene (blue) and m-xylene (green) for a thin film of the copolymer, and for a bilayer made of the copolymer capped with a PVA layer (panels a and b, respectively). Panel a in the figure shows that for the uncapped copolymer, the intensity of emission decreases to less than 10% of the initial value within 15 minutes of
exposure to all analytes, with the highest variation during the first few minutes. On exposure to dichloromethane (red line), the fluorescence is quenched completely within four minutes. The response is slower for the other analytes, with the slowest being m-xylene. On the other hand, chloroform and toluene induce similar responses. However, capping the copolymer with a thin layer of another polymer, the kinetics of the process is changed as the capping polymer rules the diffusion of the analyte into the system. Figure 1b shows that capping the system with a PVA thin film modifies completely the relative quenching effect of the vapors. The slowest response becomes that to toluene, followed by the response to m-xylene. The response to dichloromethane is still the fastest, albeit significantly slower than that observed for the uncapped copolymer film, not reaching equilibrium during the exposure time. All the quenching processes show slower kinetics than for the uncapped sensitive material, promising better sensitivity of the sensor.

Figure 1: Normalized fluorescence intensity on exposure to different vapors for a) copolymer thin film, b) copolymer thin film capped with a PVA a thin film.

4. Discussion

The decrease in the fluorescence intensity of the copolymer upon vapor exposure can be attributed to formation of the typical twisted intramolecular charge transfer state. The effect of the capping layer can be assigned to multiple factors, including the extent of the interaction between the polymer and the vapor, arising from their solubility and their molecular size.[17,18] In addition, the vapor pressure of the analyte is expected to influence the kinetics. Currently, other capping layers are being tested to get a better understanding of their effects and its correlation with polymer properties. The photo physics of the quenching mechanism accompanying vapor exposure is being investigated as well.

5. Conclusions

We demonstrate a proof of concept of selective vapor sensors based on fluorescent copolymers capped with diffusion-controlling polymer layers. Changing the barrier between the vapor and the fluorescent molecular rotors embedded in polystyrene matrix provides a means of controlling the selectivity and speed of sensing of the system. They can also serve as tools to understanding the diffusion in the capping layer.

References

Near-field luminescence of two-dimensional semiconductors

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Abstract

Two-dimensional semiconductors are ideal light sources for on-chip integration. They exhibit strong luminescence, and are capable of single-photon emission. Since the wavelength of the light is considerably larger than the physical dimensions of the emitter, near-field handling of the emission with a deeply subwavelength spatial resolution would be of great importance. Here we present fully near-field photoluminescence study of two-dimensional semiconductors, with a surface plasmon interference device used for the excitation and scanning near-field optical microscopy for the collection.

1. Introduction

Transition-metal dichalcogenides are layered semiconductors with the bulk indirect band gap transforming into the direct band gap when the thickness is reduced to a single two-dimensional monolayer. Recently, single photon emission in these semiconductors has been demonstrated, attributed to the localized defects \cite{1}. The emission is stable up to room temperature, making the two-dimensional semiconductors very attractive for prospective applications.

We demonstrate near-field luminescence of two-dimensional semiconductors with a surface plasmon polaritons used for the excitation and a scanning near-field optical microscope (SNOM) for the collection. This fully near-field approach allows to overcome the spatial resolution set by the diffraction limit and paves the way for on-chip integration of the emitters based on the two-dimensional semiconductors.

2. Excitation: Surface plasmon interference device

For the excitation of the emitter we employ surface plasmon polaritons, evanescent electromagnetic waves propagating along the dielectric-metal boundary. They combine the advantages (and disadvantages, to some extent) of optical and electronic excitation. As electromagnetic waves, SPP allow low-loss excitation and do not require contacts which can be difficult to fabricate and detrimental to the optical properties of the emitter. Due to the coupling to the conductive environment, SPP allow to achieve deeply subwavelength spatial resolution.

The experiment has been carried out using a surface plasmon interference device (SPID) \cite{2, 3, 4}. It consists of an opaque gold layer (thickness about 200 nm) on a glass substrate with thin slits fabricated using focused-ion-beam milling (Ga\textsuperscript{+} ions at 30 keV). The subwavelength thickness (below 100 nm) of the slits ensures that only SPP can pass through the slits while the far-field radiation is blocked.

![Figure 1](image-url) (a) A scheme of a SPID. The slits in the opaque gold layer illuminated from bottom act as sources of SPP that interfere at the top interface. (b) AFM image of a SPID.

Figure 1(a) shows a scheme of the operation of a SPID. The SPID is illuminated from bottom while the gold layer blocks the impinging wave. SPP are generated at the slits, propagate through the slit and form a standing wave on the top interface, where the distribution of the field is characterized by SNOM for the collection. Figure 1(b) shows an atomic force microscopy (AFM) image of a SPID.

3. Collection: Scanning near-field optical microscope

The near-field at the top of the SPID is characterized with a SNOM (NT-MDT Ntegra Solaris). The optical signal is collected with the aperture-type probe and guided through the optical fibre to the spectrometer. Details of the setup are provided in Ref. \cite{3}.

The probe can be designed so that it exhibits a polarization sensitivity \cite{3}. This is manifested in Fig. 2 which shows the field patterns for a square-like SPID. For suitable illumination, the in-plane component of the SPP field exhibits a square-like pattern while the out-of-plane component exhibits a diamond-like pattern. The diamond-like...
4. Near-field luminescence

We have used a SPID with a circular slit. A monolayer flake of WS$_2$ has been prepared by a micromechanical exfoliation from a bulk monocrystal and transferred using a polydimethylsiloxane (PDMS) dry transfer technique to the SPID. This procedure ensures that the semiconductor is not damaged during the fabrication of the slit.

Prior to the transfer, the semiconductor flake has been characterized by the optical microscopy and Raman spectroscopy to identify the areas with the monolayer thickness.

The emission of the flake recorded by SNOM for the SPID illuminated at the wavelength of 532 nm is shown in Fig. 3. A spectral analysis reveals a peak centered at the wavelength of 615 nm, in a perfect agreement with the bandgap of WS$_2$ monolayer of 2.02 eV.

5. Conclusions

We have demonstrated fully near-field luminescence of a two-dimensional semiconductor with surface plasmon interference device used for the excitation and the scanning near-field optical microscopy used for the collection. Deeply subwavelength nature of the experiment allows to characterize the emitter with the spatial resolution below 30 nm and opens the way towards the on-chip integration of the emitter.

Acknowledgement

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References


Exciton diffusion and annihilation in nanophotonic landscapes

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Abstract

Excitonic emitters in semiconductors exhibit diffusion and annihilation. Conventional nanophotonics improves light emission by providing enhancements of excitation, emission efficiency, and collection, but neglects exciton dynamics. We exploit exciton dynamics for improving emission, going beyond the localized Purcell effect. We present guidelines to benefit from diffusion and to ameliorate the effects of annihilation. We identify the dominant mechanisms for enhancement for limits of diffusion and annihilation. Controlling exciton dynamics has direct implications for light-emitting devices based on excitonic nanomaterials.

1. Nanophotonic enhancement in the presence of exciton dynamics


Here, we go beyond the localized Purcell effect to exploit exciton dynamics for improving emission. We perform numerical simulations using the surface integral equation method [5] and demonstrate that as excitons in a thin film diffuse through optical hotspots, the balance of diffusion constant and nanophotonic geometry leads to either enhanced or suppressed photoluminescence. We present guidelines to turn the usually detrimental impact of diffusion on emission into additional enhancement and to overcome the adverse effects of annihilation at high exciton densities. Finally, we identify the distinct dominant mechanisms for enhancement in the limiting cases of high and low diffusion and annihilation. Controlling such rich exciton dynamics has direct implications for efficient and high-power light-emitting devices based on excitonic nanomaterials.

References


Figure 1: Exciton diffusion and exciton-exciton annihilation affect the photoluminescence enhancement of nanophotonic structures.
Plasmons in nanostructured and corrugated 2D materials
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Abstract
In this work we theoretically investigate plasmonic excitations in 2D materials. We suggest that localized plasmons in corrugated graphene increase the surface enhanced Raman spectroscopy (SERS) response of given molecules. We also show that mirror twin boundaries (MTB) in transition metal dichalcogenides (TMDs) can sustain plasmon due to their local metallic behavior as recently experimentally highlighted.

1. Introduction
In the last decade, plasmons in 2D materials have been intensively studied due to their exceptional properties. It has been shown that localized plasmons in 2D nanoparticles exhibit stronger confinements than in their 3D counterparts. Here, we first take advantages of this confinement to explain SERS response of nanocorrugated graphene. Moreover, the existence of 1D plasmons has been theoretically suggested for which one can expect even larger confinements of light. The 1D plasmons at the edge of 2D finite domains or at the interfaces between conducting and insulating 2D materials can be viewed as the analog of the 2D surface or interface plasmons well known in metallic films [1]. Another type of 1D plasmon is associated to atomic reconstructions at the edge of nanoribbon or at grain boundaries that can be at the origin of a 1D metallic channel in 2D materials, as also shown here in a MoSe2 ribbon.

2. Method

2.1. Ab initio simulation
The dielectric function is obtained by DFT simulation in the GPAW code. The optical properties are studied using an eigenmode decomposition of the microscopic dielectric function [2]. Each mode is associated to a single plasmonic excitation which can be characterized using the spatial distribution of the potential and charge. The weight of each mode is then associated to the oscillator strength such that we can determine the optically active modes. These results can be compared with the electron energy loss spectroscopy (EELS) spectrum obtained within the same quantum framework.

2.2. Classical EELS simulations
Classical EELS spectra have been obtained using the DDEELS code based on a discrete dipole approximation method [3].

3. Results
3.1. Plasmons in corrugated graphene
Corrugated graphene with ripples around 5 nm large exhibits a different optical response compare to flat graphene. Using the eigenmode method we show that corrugated graphene can sustain several localized plasmon-like excitation on a single ripple. This is explained by the change in hybridization of the carbon-carbon bonds related to the curvature of the graphene layer. It is then suggested that these plasmons couple to molecules adsorbed on the graphene such that the SERS response is greatly enhanced as experimentally demonstrated.

Figure 1: Charge distribution of two optically active plasmons in a graphene ripple (highest carbon atoms are in yellow).

3.2. Plasmons in MTB
Mirror twin boundaries in TMDs exhibit a metallic behavior as recently demonstrated [4]. By studying a MoSe2 ribbon containing a MTB, we show that the MTB sustain a 1D plasmon at a slightly higher frequency than the main 1D plasmon arising from the metallic edge states. We suggest an effective medium approach to study more complex
systems with a high density of MTB and apply it using classical simulation of EELS.

Figure 2: Charge distribution of the 1D plasmon of the MTB (red box) in a MoSe$_2$ ribbon (black dotted box).

4. Conclusions

We have highlighted the existence of plasmons in both corrugated graphene and MoSe$_2$ ribbon. In the first case, they are due to the localization of charges in a ripple, in the second the metallic behavior of the boundaries and edges is involved. We have extended the method presented in [2] to determine the optically active plasmons and suggest an effective medium approach to study more complex systems.

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References

Gold Nanoparticle Arrays on Flexible Substrate for Stress Measurements

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Abstract

Gold nanoparticles, and gold nanoparticles arrays, have widely been used as sensors, especially in the biology field due to their plasmonic properties. They present strong coupling in the visible range which makes them easy to observe.

We therefore aim to use nanoparticles arrays to create a mechanical strain test sensor based on Fano effect.

To do so we developed techniques to deposit gold nanoparticles on flexible substrates.

1. Introduction

Gold nanoparticles are widely been used for their range of applications: drug delivery, near-field enhancement, bio-targeting, sensors [1, 2].

Their use as sensors in the mechanical field is for now mostly limited to displacement tracking with a SEM [3]. They exhibit a strong plasmonic behavior in the visible range.

By arranging them in a grating, a discrete quantum state interferes with a continuum band of states resulting in a hybrid behavior with a characteristic asymmetric sharp line-shape described by the Fano theory [4].

This spatially limited behavior is very sensitive to the pitch used in the grating, and by analogy, to sample’s stretch.

This effect can be reproduced with a flexible substrate (PDMS, Sylgard 184, Dow Corning) in order to use it as a deformation sensor.

By stretching a flexible sample, the nanoparticles will move, accordingly to the applied force (strain, shear, or a combine of the two e.g. by applying an internal pressure).

This displacement of the nanoparticles will lead to changes in the spectral response of the grating (quenching or enhancement, shift...) depending on the parameters of the initial lattice.

The fabrication processes of such samples are detailed in part 2, and a simulation is presented in part 3. Finally, we will conclude and open to new leads in the area with such techniques.

2. Fabrication processes

To develop a sample of gold nanoparticles on a flexible substrate, we imagined two different ways of deposition. The first one uses EBL to synthetize gold nano-cylinders, which are then transferred on a PDMS substrate. The second one uses SmartForce SF-Research system to deposit synthetized gold nanoparticles in a molded PDMS substrate.

2.1. Electron-Beam Lithography (EBL) synthesis of gold nano-cylinders and transfer on a flexible substrate

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Gold nanoparticles transfer on a PDMS substrate using sacrificial layers and EBL technique.}
\end{figure}

The first technique we developed consists in the synthesis of gold nanoparticles by using Electron-Beam Lithography technique, and transferring them on a PDMS substrate (a schematic representation is shown in Figure 1).

First of all, a glass substrate is prepared by evaporating a sacrificial layer of metal. The gold nanoparticles are then synthesized by an internal pressure. After lift-off, the nanoparticles are functionalized \textit{in-situ} in order to graft them to the PDMS.

It is then been mold and cross-linked. A last step of development of the sacrificial layer is done to get the final sample.

2.2. Deposition on a flexible substrate using SmartForce SF-Research

In order to improve the deposition process speed, and enlarge the field of possible applications, we also developed an other deposition process using SmartFoce Technologies system (SF-Research).
The technique is divided in two parts: first, we synthetize gold nanoparticles using the method presented by N. G. Bastús and al. [5]. The synthesis consists on a reversed Turkevich method, after which we add a growing step, by dilution and addition of gold chloride ions for several times. Simultaneously, PDMS sample is prepared with an EBL-made cones mold (Ni-Cr deposition). The negative of this cones is molded in the PDMS sample, in which we obtain nanometer-sized holes after cross-linking step. We then use the SF-Research to deposit gold nanoparticles on the PDMS substrate, by adjusting the contact angle and evaporation speed. Because of the diffusion effect, a higher concentration of gold nanoparticles will occur in the edge of the drop. This will create a force which will push nanoparticles inside the holes - dimensionned accordingly to their sizes - in which they are trapped.

3. Characterizations of the samples

Such structures have been modeled in vacuum, by using a standard FDTD model, which leads to an increase of the Fano effect at 742nm for a 700nm square grating (the corresponding simulation is presented in Figure 2). We here used 50nm height gold nanocylinders with a diameter of 200nm, arranged in a square grating.

![Figure 2](image)

Figure 2: Simulation of the absorbance of a gold nanoparticle lattice in vacuum. Nanoparticles are cylindrical with a diameter of 200nm and a height of 50nm. The spectral response shows a sharp maximum (Fano effect) at 742nm for a 700nm pitch, which can be used for stress detection.

Furthermore, the fabricated samples are characterized by SEM, AFM in order to check the transfering process. In order to compare them with the experimental data, we analysed the samples with a home-made optical setup in the visible - near infra-red - range.

4. Conclusions

Fano effect in gold nanoparticle lattices enlighten new perspectives in the field of mecano-plasmonics. Such improvements can lead to the development of high-resolution sensors (under the micron scale), with a high sensitivity to mechanical displacements. The upcoming experiments will include the analysis of different kinds of mechanical stresses (strain, shear, pressure...), and the coupling with emitters such as quantum dots.

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References

Integrated Photodetection Leveraging Plasmonic Radiation Pressure

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Abstract
We present novel integrated photodetectors based on the radiation pressure of a plasmonic mode. Light absorbed in a plasmonic or hybrid plasmonic/optical waveguide builds a voltage along the length of the waveguide via the photon-drag effect. We implement this device concept for the first time and investigate its potential for fast, broadband, and inexpensive optical detection in an integrated platform.

1. Introduction
Current flow in metallic films can be induced by the absorption or redirection of momentum carried by an electromagnetic wave, a phenomenon known as photon drag [1,2]. Since it is based in radiation pressure, this effect is naturally broadband, with a spectral range from visible to beyond far-IR. Since the photoexcitation involves only intraband conductivity, the photocurrent switching speed is fundamentally limited only by the electron momentum relaxation rate, corresponding to multi-THz bandwidths [3]. Finally, since a photon-drag photodetector is essentially simply a contacted metal film, it avoids the potential expense and toxicity of an added semiconductor (e.g. III-V) process.

The primary drawback of a photon-drag detector is sensitivity: Optical forces are second order in nature. For example, the magnetic force $J \times B$ is proportional to $v/\epsilon$, where $v$ is the electron velocity. However, the literature reports successful enhancements of photon-drag signals by optimizing the absorption of in-plane momentum of light into the metal film through the excitation of plasmonic waves [4]. In addition, Durach et al. have noted, in theory, the favorable scaling of a transduced voltage with a smaller cross-sectional area of the metal film and a stronger plasmonic mode character when operated close to the plasma frequency [3]. Reducing the characteristic feature sizes of the device has the dual benefits of increasing the photocurrent density and reducing the current-shunting effect [2]. Thus, the photon-drag effect might be particularly well suited for realizing fast and inexpensive photodetectors for integrated photonic circuits in emerging fields such as mid-IR detection.

Here, we provide the first demonstration of integrated plasmonic photon-drag photodetectors. We aim to leverage the unavoidable loss in the plasmonic system to transfer momentum to the metal. The designed operating principle is as follows: Light propagating in an optical waveguide couples to a plasmonic mode either in a metal-insulator-metal (MIM) waveguide [5] or a hybrid plasmonic-photonic

![Figure 1. Depiction of (a) MIM and (b) HPP integrated photon-drag devices. (c) Absolute value of electric field vector for the MIM plasmonic mode, calculated with finite-element frequency-domain analysis. (d) Analytically calculated Lorentz force density (Eq. 1) in the direction of propagation for the MIM waveguide, including both bulk and surface forces ($n = 3.5$).](image-url)
(HPP) waveguide [6] (see Fig. 1(a-b)). Light absorbed in the metal imparts a force in the propagation direction, thereby transducing a voltage along the length of the metal waveguide via the photon-drag effect. These devices have the potential to bring high-speed, broadband photodetection, leveraging plasmonic radiation pressure, to integrated photonics.

2. Methods

We designed the integrated plasmonic waveguides through finite-element frequency-domain simulations with a target free-space wavelength of 1550 nm. For the MIM structure (see Fig. 1(c)), a primary design goal was to minimize the cross-sectional area of the metal rails, in a physically realizable geometry, without significant radiation loss. The electric field penetrating the gold film drives absorption loss, resulting in momentum transfer to the metal.

We employed a complementary analytical examination of the optical forces in an MIM waveguide. The Lorentz force density for non-magnetic materials may take the form [7,8]

\[ F = -(\nabla \cdot P)E + \partial_t P \times B, \]

where \( P = \chi E \) is the electric polarization vector, and \( \chi \) is the material’s complex electric susceptibility. Calculations of the longitudinal components of the two terms of Eq. (1), as a function of transverse position in the MIM waveguide, appear in Figure 1(d). The components of force in the bulk of the gold, and at the interfaces, may contribute to the photon-drag effect. These calculations reveal that for a constant transverse \( H \) field, a smaller gap width and larger gap refractive index correspond to larger forces acting on the gold.

We fabricated the MIM and HPP devices based on a silicon-on-insulator platform having a silicon device layer of 220 nm (see Fig. 2). First, we patterned the silicon waveguides for on-chip routing, including an inverse tapered edge coupler. This was followed by PECVD deposition of SiO\(_2\) to embed the photonic waveguides. Afterwards, the metal waveguides and contact pads were formed on top of the silicon dioxide. Fabricated MIM structures had a gap width of 120 nm and lengths varying from 5–50 \( \mu \)m. Fabricated HPP structures had metal widths varying from 300–600 nm and metal lengths varying from 5–150 \( \mu \)m.

Continuous wave 1550 nm free-space wavelength light coupled into the silicon waveguides through a polarization controller and tapered lensed fiber. Two probes contacted the waveguide metal at the entrance and exit, respectively, and a nanovoltmeter recorded the open-circuit voltage across the waveguide length.

3. Results and Discussion

Initial testing of the integrated plasmonic photon-drag photodetectors revealed measurable voltages approximately proportional to the supplied optical power and dependent on the optical polarization in a manner consistent with the polarization dependence of coupling into the plasmonic waveguides. Measured responsivities, estimated to approach 1 mV/W, varied with device geometry. Compared to the responsivities reported by Strait et al. [2], those of the integrated device are a factor of \(~10^6\) larger, enabling the use of continuous-wave lasers and DC detection, in contrast with typical pulsed measurements found in the literature [2,4]. Through optimizations in waveguide and coupler design, we expect further improvements in sensitivities.

We are continuing to explore the fundamental mechanisms of voltage transduction, including the role of thermoelectric effects and the possible existence of the surface sensitivity and counterintuitive phenomena reported in Ref. [2]. Should the surface sensitivity be confirmed for an MIM device with slot exposed to the environment, this configuration will be a natural platform for integrated sensing of adsorbates in a gas cell or microfluidic channel. In addition, the vector quality of momentum suggests a novel application of these integrated photon-drag devices to differential photodetection. Rather than requiring two separate photodetectors and a subtraction circuit, the two ports of a plasmonic waveguide photon-drag detector together will by nature operate as a differential detector, since the signals generated at each will subtract. We will describe our process to design, fabricate, and test these novel devices, as well as the ongoing investigations into applications and underlying physical mechanisms.

References

Self-assembly of Cubic Plasmonic Nanoparticles for Unnaturally High Refractive Index at Optical Frequency

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Abstract

In this work, we demonstrate self-assembly of the cubic plasmonic nanoparticles superlattice to achieve unnaturally high refractive index (n) at optical frequencies (i.e., near infrared (NIR)). First, we (i) synthesize highly uniform gold nanocubes (Au NCs) and then, (ii) self-assemble them into 2D superlattice. Through this self-assembly approach, Au NC superlattices are successfully obtained over the large area; exhibiting n of 6.4 at the resonant (NIR), which were not reached thus far.

1. Introduction

An increase in refractive index (n) can advance various optical technologies [1,2,3,4]. Toward this, metamaterials have been rationally designed to provide unnaturally high-index; indeed, the achievable range of n particularly at microwave and terahertz (THz) has been greatly expanded by lithographic fabrication of the designed metamaterials (i.e., n of 38.64 at THz, which is much higher than naturally accessible range) [5]. Nonetheless, an increase in n beyond the natural limit is yet to be achieved at optical regimes by using concept of metamaterials. The conventional semiconducting processing cannot address the structural requirements for achieving unnaturally high n of optical metamaterials. These requirements include the arraying of sub-100 nm electric meta-atoms with a few nanometer-gaps over the large area [6].

To address this challenge of lithographic method, we use the bottom-up self-assembly of sub-100 nm plasmonic colloidal NPs, providing a versatile platform for achieving a few nanometer-plasmonic gaps over the large area. Plasmonic colloids can act as the electric meta-atoms; the induced electric dipoles (ED) in each colloid can be strongly coupled with each other throughout a few nanometer-gaps. Furthermore, the facial interfaces between colloidal meta-atom, resulting from the use of plasmonic nanocubes (NCs) in assembly, can boost the polarization (P) of these assemblies. This is because the coupling between the induced EDs is governed by capacitance [5,6]. Consequently, unnaturally high refractive-index metamaterials are successfully fabricated via lithography-free soft self-assembly methods.

2. Result and Discussion

2.1. Synthesis and Assembly of Au NCs

In this study, we use the seed-mediated synthetic methods. As shown in Fig. 1(a), we carry out the iterative growth and etching protocol to obtain highly uniform and relatively large (~60 nm) Au NCs [7]. According to our custom-built algorithm, Au NCs have about 59.5 nm length. The aspect ratio is close to 1, confirming high uniformity (Fig. 1(b), (c)).

Figure 1: (a) Schematic of the synthesis of highly uniform Au NCs. [7] (b) Scanning electron microscopy (SEM) images of the chemically synthesized single-crystalline Au NCs with sizes of 59.5 nm (c) Au NCs size and aspect ratio quantified by custom-built algorithm.

For the close packing of Au NCs into monolayer, we used the water-oil interfacial self-assembly methods (Fig. 2(a)) [8], comprising of (i) forming an interface between aqueous Au NCs suspension and oil (i.e., hexane) and (ii) continuously adding ethanol into the already prepared aqueous solution, giving rise to the accumulations of Au NCs selectively at the water-oil interface. Above the critical concentration of ethanol, the crowded Au NCs were closely packed and ordered into a monolayer, then we transferred the assembled Au NC monolayer onto the glass substrate (Fig. 2(b))
2.2. Theoretically and experimentally analyzed effective refractive index ($n_{\text{eff}}$)

We predicted the effective refractive index of the assembled monolayer of 60 nm Au NCs using numerical simulation and $s$-parameter retrieval method [9]. In addition, we experimentally measured the effective refractive index ($n_{\text{eff}}$) by using ellipsometry. As shown in Fig. 3, the achieved $n_{\text{eff}}$ value of 6.4 was peaked at the resonant wavelength (NIR), which is higher than those of naturally occurring materials.

![Figure 3: Theoretically predicted and experimentally measured $n_{\text{eff}}$ values of the self-assembled 60 nm Au NC monolayer at near-infrared (NIR).](image)

3. Conclusions

The self-assembly of Au NCs provided $n_{\text{eff}}$ of 6.4 at the resonant wavelength (NIR). To the best of our knowledge, this achieved value is among the highest. This unprecedentedly increased $n_{\text{eff}}$, in conjunction with soft fluidity of our method can facilitate the innovation of various optoelectronic devices.

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References

CdZnO nanoparticle coating on GaAs for IR field enhancement.

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Abstract

In this work, we study the plasmonic response of CdZnO nanoparticles grown on GaAs in the mid-IR range of the spectrum. We measured the transmittance of the system and evaluated the field-enhancement profile of the system, identifying two plasmonic modes. Finally, we briefly discussed the potential applicability of this NP coating in photonic devices, once demonstrated the penetration of the electrical field within the substrate supporting the NPs.

1. Introduction

For decades, the range of the EM spectrum accessible to the field of plasmonics has been limited to the visible and UV. This situation has promoted the research of alternatives to metals (the most used plasmonic materials) best suited for the IR. Among those, Transparent Conductive Oxides such CdO appear as perfect candidates due to their plasma frequency (\(\omega_p\)) tunability via doping or alloying. As demonstrated by our group [1], the electro-optical properties of CdO can be further improved by introducing a 10% of Zn into a ternary compound. CdZnO showed a high plasma frequency (over 9000 cm\(^{-1}\)) with a relatively high mobility (110 cm\(^2\)/V·s), values fully compatible with a plasmonic behavior in the IR. In this work, we study the Localized Surface Plasmon (LSP) resonances in CdZnO NP systems with a perspective in the IR potential device applications.

There is a big advantage in using isolated NPs instead of grown thin layers for plasmonic purposes. In the last case, complex coupling techniques such as gratings or high index prisms are needed in order to excite the surface plasmonic modes. By contrast, LSP in NP can be directly coupled by light, increasing the technical versatility of NP systems [2]. GaAs was selected as substrate responding to the intention of demonstrating the viability of CdZnO in future IR photonics. GaAs is a well-stablished semiconductor in photonics technology with a wide range of applications including laser, solar-cells and IR photodetectors. By adding a CdZnO NP coating we expect a plasmonic-based E-field enhancement that can potentially improve the efficiency of light absorption-based devices.

2. Materials and methods

The CdZnO nanoparticles were grown by Chemical Vapor Deposition (CVD) on semi-insulating GaAs at 330ºC. Transmittance spectra were measured with a Fourier Transform Infrared (FTIR) spectrometer at 0, 45 and 80 degrees. The experimental results were reproduced by computational simulation using a Discrete Dipole Approximation (DDA) based software. The dielectric function of CdZnO material was modelled agreeing with the study of Tamayo-Arriola [3] for thin films of the compound. NPs were modelled as isolated spherical caps with a 120 nm radius and a high of 80 nm. Transmittance was calculated based on computational extinction cross sections by the Lambert-Beer law [4].

![Figure 1: SEM images of the experimental sample.](image-url)

In order to completely characterize the nature of the plasmonic resonances found in the NPs, the field distribution of the electric fields was also calculated, according to the simulations previously performed.

3. Results and discussion

As shown in figure 2, two plasmonic resonances were found at 1900 and 3500 cm\(^{-1}\). Observing the differential angle-depending response, these two LSP modes can be described
according with the direction of the electron oscillations in the NPs. The higher energy mode is maximized for angles close to 90° in our p-pol measurements, being the incident electric field perpendicular to the substrate surface. The lower energy one reaches its maximum value at normal incidence (parallel electric field) with a vanishing high energy mode. Figure 2 also highlights the excellent agreement between the experiment and the simulation results, demonstrating that our simplified (one size, one shape and isolated NPs) model can fully explain the emergence of both modes in our system.

Figure 2: Transmittance of the experimental sample. Experimental data are shown as dark lines in contrast with the computational calculation (light lines).

The calculated field distributions shown in figure 3 reveal that different nature of the previously described resonances. The low-frequency mode finds its bigger field enhancement in the lateral edge of the spherical cap, defining a plane parallel to the GaAs substrate. The simulation also shows an exceptional penetration in the substrate, with outstanding values close to the NP edge and maintaining an enhancement factor of 2 at 50 nm of depth. By contrast, the perpendicular mode doesn’t reach similarly high values, but also provides an interesting field magnification at closer distances. In this last case, the maximum-field describes the expected profile with the highest values located in the base and the apex of the cap. Under those circumstances, it is worth noting that the absorption intensity scales with the square of E-field values so improvement in absorption by an active substrate can be superior to the values in figure 3 for a real device scenario.

Figure 3: Field enhancement factor for the low (a) and high (b) energy modes. The factor is defined as a quotient of the electric field obtained in presence of NP and the field in its absence. Simulations were performed for an incident p-polarized wave with an incident angle of 45°.

With these two field-direction selective modes, our studied NP coating is revealed as a solid promise for future IR absorption-based photonics. With our material, the field enhancement provided by the NP in the substrate meets the bigger strength of TCOs when compared with traditional metal-based plasmonics: the tunability of LSP via \( \omega_p \) modulation. Furthermore, the E-direction selectivity of the modes, opens the gates to new possible uses such as direction-sensitive filters.

4. Conclusions

We show here that spherical cap shaped CdZnO NPs grown on GaAs support two LSP modes according with two possible directions of plasma oscillations. These LSP are highly selective to the direction of the incident field (i.e. in plane or out of plane E-field), but in both cases provide a decent magnification of the field inside the GaAs substrate. These previously discussed properties define our CdZnO NP coating as an excellent method to achieve high intensity fields within the substrate, with great potential for future IR photonic devices.

References


Demonstration and Tuning of Tamm Plasmons at the Interface with Metasurfaces

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Abstract

We demonstrate experimentally that Tamm plasmons can be supported by a dielectric mirror interfaced with a metasurface, a discontinuous thin metal film periodically patterned on the sub-wavelength scale. Not only do Tamm plasmons survive the nano-patterning of the metal film, but they also become sensitive to external perturbations, as a result. In particular, by depositing a nematic liquid crystal on the outer side of the metasurface we were able to redshift a Tamm plasmon by 35 nm, while electrical switching of the liquid crystal enabled us to tune the wavelength of this notoriously inert excitation within a 10 nm range.

1. Introduction

A Tamm plasmon (TP) is a localized resonant optical state, a quasi-particle, which exists at the interface between a metal and a dielectric (or semiconductor) Bragg mirror. It was theoretically predicted in \cite{1} and experimentally observed in \cite{2}. The TP dispersion lies completely within the light cone and therefore, in contrast to an ordinary surface plasmon polariton, a Tamm plasmon can be excited with both TE- and TM-polarized light at any angle of incidence \cite{1}. Another advantage of a Tamm plasmon over a surface plasmon polariton is that the former appears to be almost insensitive to dissipative losses in the metal film since its electromagnetic fields are localized predominantly in the non-absorbing Bragg mirror \cite{3}. Because of its robust nature, a Tamm plasmon has been regarded as a viable alternative to conventional surface plasmons in a wide range of applications, including optical switches, semiconductor lasers and light emitters, and temperature sensors. For many practical applications it is important to realize an external dynamic control over the TP wavelength. Such a task, however, presents a formidable challenge since the fields of a Tamm plasmon reside inside the Bragg mirror and, therefore, are not accessible from the outside. The approaches proposed so far involve the integration of a control element into the very structure of the Bragg mirror, which is not always feasible.

2. Results and Discussion

Here we report on the first experimental observation of a Tamm plasmon at the interface between a Bragg mirror and a nano-patterned metal film acting as a non-diffracting optical metasurface. We also found that the discrete framework of the metasurface exposed Tamm plasmon to external perturbations, such as changes of the refractive index in an adjacent medium, which enabled us to dynamically control the wavelength of this weakly coupled optical state in a simple yet efficient way.

Figure 1: (a) Schematic of the structure. The white arrow shows the direction of rubbing, $n$, which controlled the alignment of LC in the cell. (b) SEM image of a fragment of the metasurface fabricated on top of a Bragg mirror.

Figure 1a presents the design of the structure that was used to observe Tamm plasmons in our experiments. The structure was based on a silver-coated dielectric Bragg mirror designed to exhibit a 0.5 $\mu$m wide reflection band centered at the wavelength $\lambda = 1.45 \mu$m. It was formed by a stack of alternating 11 layers of Nb$_2$O$_5$ (159 nm) and 10 layers of SiO$_2$ (246 nm). The silver coating had the thickness of 37 nm. A 30 $\mu$m x 30 $\mu$m patch of the silver film was turned into a metallic metasurface by nano-patterning the film with a focused ion beam. The pattern of the metasurface featured a square array of 550 nm large disks with the period of 600 nm (see Fig. 1b), which rendered the nanostructure as non-diffracting above
$\lambda = 1.34$ $\mu$m, i.e., well within the reflection band of the Bragg mirror.

Figure 2: (a) Experimental reflectivity spectra of the Bragg mirror acquired while it was in a pristine state (blue), after it was interfaced with a continuous silver film (black), and after the silver film was nano-patterned to become a metasurface (red). Grayed area marks the band of Tamm plasmons. (b) Wavelengths of Tamm plasmons measured for the silver film and metasurface as functions of applied voltage after the structure was integrated with a liquid-crystal cell. Dashed curves are a guide for the eye.

Figure 2a compares the reflectivity spectra taken at three different areas of the sample corresponding to an uncoated (i.e. pristine) Bragg mirror, a Bragg mirror with a continuous silver film and a Bragg mirror with the metasurface. As per design, the pristine mirror is seen to exhibit a characteristic, spectrally flat reflection band spanning from about 1.22 to 1.66 $\mu$m. The reflectivity spectrum of the silver-covered area of the mirror reveals the appearance of a Tamm plasmon – a narrow reflectivity dip located within the band of the pristine mirror and centred at $\lambda = 1.49$ $\mu$m. Intriguingly, the Bragg mirror, when combined with the metasurface, appeared to support Tamm plasmons as well, exhibiting a similar reflectivity dip in the same spectral window. These results represent, to the best of our knowledge, the first experimental evidence that Tamm plasmons can be also observed at microscopically discontinuous metal films, surviving the segmentation of the films into nanometer-sized patches.

While the nano-patterning of the silver film did not affect the ability of the structure to support a Tamm plasmon, it naturally exposed the surface of the Bragg mirror. Consequently, that should have locally broken the confinement of the Tamm plasmon, allowing a direct access to its fields (which would otherwise remain difficult to couple to, residing under the continuous silver film). To verify that assumption experimentally, we introduced an electrically controlled liquid-crystal (LC) cell into the structure of the sample, as schematically shown in Fig. 1a. The cell was vacuum-filled with a LC mixture E7 and set to induce planar alignment of E7 in the off state. By increasing the voltage across the cell we gradually switched E7 from the planar to homeotropic state, in which LC molecules are oriented perpendicular to the mirror. Due to anisotropy of LC molecules the switching of the cell was accompanied by the change of the refractive index but only for polarization parallel to the direction of rubbing ($E || n$, Fig. 1a).

Figure 2b confirms that the Tamm plasmon excited at the interface with the metasurface appeared to be quite sensitive to the presence of the liquid crystal. In particular, filling the cell with E7 red-shifted the TP reflectivity dip by about 35 nm ($E || n$) and 25 nm ($E \perp n$), which was consistent with the increase of the refractive index above the metasurface. Also, for $n$-polarized illumination the TP reflectivity dip was seen to blue-shift as soon as the applied voltage had exceeded 0.5 $V$. The extent of the shift reached 10 nm at 2.0 $V$ and corresponded to the change of LC from planar to homeotropic state. By contrast, for unstructured silver film the spectral location of the Tamm plasmon was unaffected by filling the cell with E7, as well as by changing its state in the cell (see Fig. 2b). As noted above, such behavior resulted from strong confinement of the TP fields, which were effectively screened by the unstructured film from external perturbations.

3. Conclusions

We showed experimentally that a Tamm plasmon could be excited at the interface between a dielectric Bragg mirror and a nano-structured non-diffracting metasurface. Our findings indicate that the metasurface, through its discrete framework, had enabled an external access to, otherwise, weakly coupled fields of the Tamm plasmon. We found that placing a dielectric, such as a liquid crystal, in direct contact with the outer side of the metasurface red-shifted the TP wavelength by as much as 35 nm, while no spectral shift could be detected when the liquid crystal was applied to a continuous metal film in the conventional configuration. Furthermore, we managed to tune the TP wavelength within a 10 nm range by changing the LC refractive index above the metasurface with an externally applied electric field. We argue that the demonstrated ability to control the spectral location of Tamm plasmon opens up a viable route to exploiting this resonant optical state in a number of real-life applications, including optical switching, enhancement of optical nonlinearity, lasing and light emission, and surface-enhanced spectroscopy.

Acknowledgements

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References

Electromagnetism and Plasmon-Enhanced Light–Matter Interactions at the Nanoscale

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Abstract

We present a theory for quantum nanoplasmonics that incorporates nonlocality and quantum effects like electronic spill-out and surface-enabled Landau damping, while also including retardation [1]. Focusing on the planar and sphere geometries, we derive analytical expressions for the nonclassical scattering coefficients, from which the optical response of the systems can be unambiguously determined. We compute the systems’ plasmonic excitations and investigate the role of quantum surface corrections to plasmon–emitter interactions, e.g., Purcell enhancement, dipole-forbidden transitions rates, and plasmon-mediated energy transfer [1].

1. Introduction

In this work, we provide a theoretical framework that remedies the shortcoming of classical electrodynamics in the mesoscopic regime, and, crucially, whose validity spans the intermediate regime where both quantum and classical effects coexist [1].

2. Results and Discussion

We develop a theory which rigorously accounts for quantum nonlocal effects in quantum nanoplasmonics, specifically, nonlocality, electronic spill-out, and surface-assisted electron-hole pair generation (known as Landau damping). In particular, we further develop and extend the formalism of Feibelman’s $d$-parameters [1–4], and derive analytical expressions for the nonclassical scattering coefficients—$\{r_{TM}, r_{TE}\}$ and $\{a_{TM}^{l}, b_{TE}^{l}\}$, for the planar interface and for metal spheres, respectively—with TDDFT-level accuracy to leading-order. Using these nonclassical scattering coefficients, we unambiguously determine the far- and near-field optical responses of the considered plasmonic structures. Our approach allows a simultaneous account of both quantum mechanical phenomena and retardation effects. Our calculations show that the simultaneous treatment of quantum effects and retardation is indeed essential for an accurate description of plasmons and plasmon-enabled phenomena in systems located in the blurred “classical–quantum boundary”. In good agreement with experiments [2, 5], we predict nonclassical redshifts (blueshifts) of the plasmon resonances in simple (noble) metals accompanied by nonclassical damping, the latter being consequence of surface-enabled plasmon decay into electron-hole pairs. Moreover, we further investigate the impact of the above-mentioned quantum surface corrections in the context of plasmon–emitter interactions, where we find that these effects impose bounds to the enhancement of the electromagnetic local density of states (LDOS), modify dipole-forbidden transitions (namely, electric multipolar and two-photon processes), as well as plasmon-mediated energy transfer between two emitter.

3. Conclusions

In summary, our theoretical framework provides a comprehensive account of both plasmons and plasmon–emitter interactions at the nanoscale, that is, in the regime of quantum nanoplasmonics. Therefore, we show that our theory constitutes a simple, rigorous, and unified platform to incorporate quantum effects in nanoplasmonics [1].

Acknowledgement

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Figure 1: (a) Illustration of the $d$-parameters obtained from TDDFT for a $r_s = 4$ jellium, together with an artistic impression of the quantum mechanical spill-out of the induced charge density in response to an external potential. (b) Classical and quantum $\text{Im } r^TM$ associated with a planar dielectric–metal interface. (c) Classical and quantum Purcell enhancement experienced by a perpendicular dipole emitter at for different emitter–planar interface separations. (d) Classical and quantum extinction cross-sections for jellium plasmonic spheres. (e) Classical and quantum Purcell enhancement experienced by a radially-oriented dipole near metal spheres of varying radii (at a fixed $h = 10$ nm emitter–surface separation).

References


Doping an Eutectic 3D Material to get Plasmonics Effects

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Abstract

Due to the development of new manufacturing technologies and the increasing availability of nanomaterials, plasmonics has become an emerging field of photonic research. Although the fabrication of metal elements has already been widely demonstrated, the development of three-dimensional plasmonic materials progresses slowly. Hence, we report the development of a eutectic compound that incorporates nanometric silver to provide surface plasmonic resonance around 600 nm.

1. Introduction

Plasmonics is currently one of the fastest developing fields due to its role in improving the optical properties of materials in different fields, such as increasing the efficiency of solar cells, in the treatment of cancer, in the improvement of hard drives and lasers and in the diagnosis of domestic use. To achieve an increase in plasmonic effects in the local field, localized surface plasmonic resonance (LSPR) or surface plasmon propagation, an interface is needed between two media: plasmonic (metal type) and dielectric. It is at this point that eutectic materials play an important role, since they allow different materials to be combined in a single body with a self-organized micro/nano structure. Our approach consists of direct solidification for the creation of eutectic with plasmonic properties by using the "micro-pulling down" technique. This technique adds the possible dispersion of nanoparticles (of varying chemical composition, size and shape) and the possibility of co-doping with other chemical agents such as, for example, optically active rare earth ions or quantum dots. Thus, greatly expanding the ability to modify at our whim the base properties of these materials. Within the variety of eutectic, we choose the eutectic composition of Bi₂O₃-CuO, based on bismuth oxide (Bi₂O₃) for its excellent optical qualities such as a wide bandgap, a high refractive index, high permittivity and good conductivity, and with a melting temperature of 780°C [1] which should be enough to avoid the Silver Nanoparticles (AgNPs) melting [2].

2. Materials and Methods

The eutectic material Bi₂O₃–CuO material was obtained by the micropulling down method [3,4] in a nitrogen atmosphere from pure powders of bismuth oxide (Alfa Aesar, 99.99% purity) and copper oxide (Alfa Aesar, 99.95% purity). All the mixed powders were ground together with isopropanol and dried. The eutectic material was grown by the micro-pulling down method with different pulling rates (0.2, 2, 10 mm/min). Detailed growth and preparation methods have been described in previous works from our group [5]. For the doped material with AgNPs (SkySpring, Ag, 99.95%, 20-30 nm) concentrations from 0.2 to 5% in molar mass is added and produced in the same way. In both cases we obtain a rod with the same external appearance like in Figure 1.

Figure 1 Photography of as-grown rod with 2 mm/min.

The structure and properties of the obtained material are investigated by optical microscopy, scanning electron microscopy, as well as X-Ray diffraction. Moreover, the absorption edge of the material is being measure with the help of a microspectrophotometer CRAIC from 400 to 800 nm in search of plasmonic resonances.

Figure 2 SEM image of Bi₂O₃-CuO surface
3. Results and Discussion

The as-grown Bi$_2$O$_3$–CuO material is characterized by a three-dimensional micro-/nanostructure of CuO-Bi$_2$CuO$_4$ containing phase in a Bi$_2$O$_3$ matrix. From the electron microscopy characterization of the samples we could observe a similar microstructure in both samples, without (Figure 2) and with AgNPs (Figure 3), meaning that this quantity of Ag does not affect the main microstructure of the Eutectic Material. The X-ray characterization shows the structure of Bi$_2$CuO$_4$ and Bi$_2$O$_3$ but no traces of other phases like CuO or Ag. From the normalize spectrum of the samples absorbance (figure 4), we confirm the absorption edge of the Bi$_2$O$_3$ around 420-430nm, and we are able to observe a slightly increment in absorption from 450 to around 700nm for the samples with AgNPs[6]. The increase in absorption is more visible after annealing the sample with AgNP on air [7]. There are two possibilities to explain this phenomenon, one it is that during the heating some AgNPs melted and with the annealing we were able to produce more “in situ” or could be due to the mobility and aggregation of some nanoparticles due to the thermal energy during the annealing. Further research would be needed to discern the correct mechanism of increased absorbance.

4. Conclusions

We present the easily obtention of a eutectic material, Bi$_2$O$_3$-Bi$_2$CuO$_4$ with low melting temperature enough to be able to dope it with AgNPs applying the micro-pulling down technique. This approach may enable rapid and cost-efficient manufacturing of materials with the possibility of doping them with other NPs or Qdots, allowing single or multiple resonances at various wavelength ranges, in order to enhance different optical processes.

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References

Boosting Faraday rotation in a one-dimensional coupled resonator magnetoplasmonic structure made by silica matrix doped with magnetic nanoparticles

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Abstract
The present study aimed to evaluate the magneto-optic Faraday rotation of one-dimensional coupled resonator magnetoplasmonic structure by metallic cover layer in each resonator. To this purpose, transfer matrix method was used where crystals made by SiO2/ZrO2 or SiO2/TiO2 doped with magnetic nanoparticles using sol-gel process in different configurations and use and 10-nm thick gold or silver layer for the excitation of the surface plasmon polaritons (SPPs). Tamm plasmons are surface modes that result from forcing the field to be confined at the metal-dielectric interface via a method different than total internal reflection. Optical Tamm states can be formed in both the TE and TM polarizations. Based on these modes, a wide range of wavelengths is detected by which the figure of merit increases due to the interaction of light with Tamm plasmons and surprisingly the flat optical window in this region in addition to the main resonance. These structures can open a new gate for enhancing performance of the magneto-optic devices.

1. Introduction
To achieve new functionalities, multilayer’s magneto-photonic crystals have attracted a great deal of attention due to their applications in designing and constructing magneto-optical devices like as modulators [1], sensors, wavelength division multiplexing [2], isolators and the like. In these structures, reaching a high and multi-channel magneto-optical (MO) rotation accompanied by enhanced transmission plays a significant role in motivating scientists to design waveguides based on these structures. In this regard, decreasing the total thickness introduced as one-dimensional coupled resonator magneto photonic crystals (1D-CRMPC) is regarded as one of the main waveguides which can help the researchers to reach the objective [3]. This efficient structure is designed based on the famous coupled resonator optical waveguide and formed by placing MO resonators in a linear array in order to guide light from one end of the chain to another by photon hopping between adjacent resonators. In these structures, each resonator consists of dielectric and magneto-optical layers. Photons can hop from one tightly confined mode to the neighboring mode due to their weak interaction and accordingly the electromagnetic waves propagate through coupled cavities. Furthermore, due to the strong optical confinements in resonators, 1D-CRMPCs allow low group velocity at the photonic bandgap (PBG) zone, yielding an enhanced MO rotation.

Recently, the combination of plasmonics with other material properties has become increasingly appealing. In particular, magnetoplasmonics and magnetophotonics are emerging areas that aim at combining magnetism, plasmonics and photonics to find new ways of controlling the properties of plasmons using magnetic fields or vice-versa, to control magnetic properties with light. The enhancement of optical confinement in nanometer scale and accordingly light-matter interactions and increased MO rotation are made possible by plasmonics in other new categories named as magneto-photonic structures. In these structures, plasmonic media like noble metal nanostructures play an important role to offer interesting possibilities when combined with the MO media to confine and enhance electric fields and finally magneto-plasmon activity. A large number of studies have been reported on the use of localized surface plasmon resonance, propagating surface plasmon and Tamm plasmons (TPs) as non-propagating surface states.

In the present study, a new structure is introduced based on the combination of plasmonic media and 1D-CRMPC structure as one-dimensional coupled resonator magneto photonic crystals (1D-CRMPC) to evaluate the effect of MO response of this new structure.
2. 1D-CRMP structure

One-dimensional coupled resonator magneto photonic crystals (1D-CRMP) is formed by placing alternation of magneto-optical layers (SiO2/ZrO2 or SiO2/TiO2) doped with magnetic nanoparticles using sol-gel process with a high refractive index and low index air layers. The central layer corresponds to a defect that allows light to pass through the center of the photonic band gap. Our structure consists of a thin layer of gold, a metal that exhibits both a plasmonic behavior, on end of a 1D coupled resonator magneto photonic crystals (Fig. 1).

![Figure 1: Schematic of 1D photonic crystal structure made with magneto-optic layers with one defect.](image)

The structure is characterized by a background index of 1.57 and an air-to-air refractive index = 1. The thickness of the layers of material is d1 = 258 nm and the gap width is d2 = 387 nm with (a = d1+d2). The central layer corresponds to a defect characterized by a width (d def = 2*d1). Fig. 1 illustrates the 1D-CRMP structure used for the study.

In the representation Fig. 2 (a) we have demonstrated the presence of photonic bandgap in 1D photonic crystals compound of SiO2/ZrO2 or SiO2/TiO2 made by sol-gel process.

![Figure 2: The Faraday rotation spectra](image)

In order to investigate the properties of photonic band gap and defect mode(s) of the structure regarding the various magneto-optical defect layer positions, we produced the Fig. 2. This figure shows the transmittance and Faraday rotation spectra of the considered structure.

3. Conclusions

In this paper, we represent a new design for magneto-photonic crystal platform. We have used a new kind of artificial magneto-optical materials (SiO2/ZrO2 or SiO2/TiO2 matrix doped with magnetic nanoparticles) in magneto-photonic crystals as a magnetic defect layer, characterized by Low refractive index material 1.51. This magnetic layer can be realized by sol-gel process. The present study aimed to evaluate the effect of metallic cover layer on the MO Faraday rotation, ellipticity, transmittance, along with the phases of one-dimensional coupled resonator and coupled resonator magneto-optical waveguide.

References

Embedded Annular-Hole Arrays Enabling Multiband Near-Zero-Index Transmission at Near-Infrared

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Abstract
An annular-hole periodic arrays enabling high-efficiency transmission in multiple bands are studied at near-infrared. Up to four subwavelength transmission bands can be obtained by placing several annular holes within each unit cell. High efficiency in transmission is achieved due to near-zero-index behavior at the cutoffs of the plasmonic modes propagating along the coaxial wave guide channel.

1. Introduction
The annular-hole arrays have been known for their capability to enhance transmission through subwavelength apertures, as compared to the conventional, e.g. circular-hole arrays [1]. High efficiency in transmission has been obtained even at a rather large thickness. This feature is preserved in a very wide frequency range that extends from microwaves to the near-infrared, whereas contribution of plasmonic effects is important for its upper part and does not appears for the lower one. At near-infrared, strong transmission in annular-hole arrays is often associated with circular surface plasmons [2], whose properties are not yet exhaustively studied. Recently, the array embedding concept has been proposed [3].

In this paper, we overview the main effects in transmission through and reflection from the embedded annular-hole arrays. These arrays differ from the conventional ones in that several annular holes are placed concentrically in each unit cell, in order to create an array representing a combination of several embedded arrays. It is demonstrated that such a design allows us to obtain several high-efficiency transmission bands in the diffraction-free regime. Each band corresponds to the holes of a certain radius, while the maximum transmission is obtained at near-zero phase advancement along the coaxial channel at the expected cutoffs (frequency-domain thresholds) of the plasmonic modes. Effects of array thickness, permittivity of the material filling the holes, and number of the annular holes per unit cell were studied. The numerical study has been conducted by using CST Studio Suite.

2. Results and Discussion
The emphasis in the numerical study was put on checking the following guesses: (i) annular holes of each of the radius value may create a separate transmission band, which is weakly affected by the holes of other radii, and (ii) high-efficiency transmission appears at the cutoffs of the waves propagating along the coaxial channels. The following set of geometrical parameters is considered as the basic set: period, \(a=800\) nm, thickness, \(t=200\) nm, slit width, \(w=10\) nm, mid-radii of the slits, \(r_1=325\) nm, \(r_2=255\) nm, \(r_3=185\) nm and \(r_d=115\) nm. The array material is silver. The slits are not filled (\(e_m=1\)). The structure is illuminated with a normally incident plane electromagnetic wave. General geometry and sample transmission results are presented in Fig. 1.

![Figure 1: Geometry of unit cell (front view) and transmission (\(|S_{11}|\)) through the periodic array with the basic set of geometrical parameters (blue solid line) and the arrays with a one hole per unit cell, i.e. 1st (red dashed line), 2nd (green dash-dotted line), 3rd (black dotted line), and 4th (dark-blue dotted line) hole, at normal incidence.](image)

Four transmission bands are observed at \(a/\lambda<0.55\), according to the number of the slits within a unit cell, see Fig. 1, left panel. To prove that each band is mainly created due to the slits of one of the radii values, \(r_i, i=1,2,3,4\), transmission is also presented in the case when only the 1st slits, only the 2nd slits, only the 3rd slits, or only the 4th slits are preserved, whereas the remaining slits are assumed to be filled with silver. As expected, the structures with one hole per unit cell show just one transmission band within the same frequency range. Moreover, spectral location of each of the maxima of the structure with four slits per unit cell well coincides with a maximum of one of the structures with one slit per unit cell. Hence, each slit works in transmission more or less separately from the others.

For further evidence, Fig. 2 presents electric field distribution for the three first maxima. The observed behavior of magnitude clearly indicates the dominant role of the holes of one of the radii values for each of the
maxima. It also indicates a very weak phase change along the waveguide channel that is confirmed by the performed analysis of phase distribution [3].

Figure 2: Electric field distribution at the first (left panel), second (middle panel), and third (right panel) maximum of transmission; propagation is from left to right; wider slits than in the basic set of parameters ($w=30$ nm) are taken for a better illustration.

Figure 3: Transmission ($|S_{11}|$) for the array with four holes per unit cell at $a = 800$ nm; solid blue line - $t = 50$ nm, dashed red line - $t = 100$ nm, dash-dotted green line - $t = 200$ nm, dotted black line - $t = 400$ nm, solid violet line - $t = 600$ nm.

Near-zero phase advancement yields the near-zero-index behavior, as occurs at cutoffs of waveguide modes [4]. As one of consequences of this behavior, dependence of transmission on the array thickness may become weaker or even disappear. Figure 3 presents an example for the 1st and 2nd maxima, when $t$ is varied from 50 nm to 600 nm. It is observed that at $w=10$ nm the 1st maximum is not shifted, while the 2nd one is weakly shifted. A weak shift is also observed for the both resonances at $w=30$ nm. It occurs despite a 16-fold difference in thickness value. Even at $t=600$ nm, transmission shows a high efficiency. This regime can be considered as zero-order Fabry-Perot resonance, which is spectrally shifted as compared to the case of Fabry-Perot etalon (i.e., from zero frequency). Clearly, near-zero-index transmission bands may co-exist in one structure with conventional (non-zero-order) Fabry-Perot transmission bands which appear at higher frequencies. It is also possible that a near-zero-index band created due to a smaller-radius slit is located quite close to a non-zero-order Fabry-Perot band created due to a larger-radius slit. Therefore, various combinations of operation modes, including unusual ones, are possible. Multiple reflection bands that are complementary to the multiple transmission bands have been analyzed in detail.

A parametric study has been conducted in order to clarify the effects exerted by variations in permittivity of the material filling the holes and by the number and location of the slits within a unit cell. The study of the permittivity variations from 0.1 to 20 indicated two main features. First, the larger the permittivity is, the lower is the frequency at which the near-zero-index transmission band appears. Second, the larger the permittivity, the less efficient the transmission at the maxima is. Filling narrow slits with an ENZ material, as suggested in [5], leads just to a weak transmission enhancement, as compared to the considered case with vacuum (air) in the slits. The reason is that the coaxial channels themselves work in a near-zero-index regime. In addition, the capability in subwavelength-scale multiband transmission is weaker in case of ENZ filling, because of a quite strong blueshift of the transmission maxima.

The specifics of coupling of the incident wave for different filling materials is presently under study. The question regarding possible compensation of an efficiency decrease for high-$\varepsilon$ filling materials has to be answered. Possible connection of the observed and expected features to the earlier developed concept of supercoupling and squeezing into very narrow waveguide channels filled with an ENZ material [5] is being examined. Other parts of our ongoing study include effects of the incidence angle and effects of the number and location of the slits within unit cells, as well as their shape. Design of the structures appropriate for experimental study is in progress.

3. Conclusions
To summarize, near-zero-index regime occurring at the cutoffs of the modes propagating along the coaxial wave guiding channels can be responsible for high-efficiency transmission through the annular-hole periodic arrays that are normally illuminated by plane waves, at near-infrared. Multiple near-zero-index bands in the diffraction-free regime can be obtained by using several annular holes of different radii, within each unit cell. Nearly zero phase advancement allows us to obtain transmission bands whose spectral location is weakly sensitive to the variations of array thickness. The obtained results contribute to a new insight on the physics and application potential of annular-hole arrays and serve a proper basis for design of the structures for experimental validation.

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References
Modelling Nanostructures for Application in Plasmonically Enhanced Hot-Electron Devices

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Abstract

Here we design nanostructures to have strong, tunable absorption in Au nanoparticles (NPs) for application in hot electron devices. Using 2D optical modelling, we show the tunability in small NPs absorption in the infra-red spectral region by mounting NPs on grating structures. We demonstrate that introducing a thin dielectric layer between the NPs and the gratings can increase the absorption in the NPs up to 3.8-fold.

1. PEH Devices

Plasmonically Enhanced Hot Electron (PEH) devices are a new category of optoelectronic devices based on excitation of hot electrons over a Schottky barrier. PEH devices have attracted interest for applications such as tailored photodetectors [1,2], solar energy conversion [3], photocatalysis [4], and water splitting [5]. The efficiency of PEH devices depends on the absorption of incident photons in metal nanostructures, generation of hot-electrons and collection of them by injection over the Schottky barrier. The internal quantum efficiency (IQE) of PEH devices is typically a few percent on resonance [5]. Theoretical work by Govorov and colleagues has shown that the rate of hot electron generation is dependent on the size of the NPs [6]. Small metal nanoparticles with diameters <10 nm have the highest generation rates which could mitigate the low IQE of hot-electron devices. Reineck demonstrated experimentally a 4-fold increase in IQE of PEH photodiodes if the size of Au NPs was decreased from 40 to 5 nm [7]. However, arrays of small NPs have limited absorption and the resonance wavelength cannot be easily tuned. In this work, we demonstrate optical methods to increase and tune the absorption in small NPs for application in PEH devices.

Fig. 1a shows a schematic of a PEH photodetection system and 1b: Calculated absorption in Au NPs with varying diameter, d, and periodicity, L = 20 nm, on a flat Au layer.

We modelled hemispherical NPs in nanostructures as semicircles with diameter (d) and period (L). Fig. 1b shows the calculated absorption spectra in only the Au NPs by integrating the power loss density over the volume of NPs for different size of NPs on a flat Au layer with periodicity, L = 20 nm. The results show that arrays of NPs with diameter, d = 10 nm demonstrate relatively low absorption of 24.5% at a resonant wavelength of 568 nm. In order to tune the resonant wavelength of small Au NPs, we mount them on Au gratings, shown schematically in Fig. 2a.

2. Results and Discussion

In this section, we will introduce different nanostructures for application in PEH devices. Due to time and memory requirements, we model the nanostructures in 2D simulations, illuminated by a plane wave with TM polarization (electric field parallel to the plane of incidence) and variable wavelength, at normal incidence. Periodic boundary conditions are used on the side walls and the width of the unit cell is set equal to the periodicity of the structure. Dielectric constants of Au (n, k) were taken from the data of Johnson & Christy [8]. The refractive index of the semiconductor was fixed to n = 2.5.

Fig. 2b shows the calculated absorption in Au NPs mounted on the gratings, for different periodicities, L, and width of...
gratings, W = 0.8L, (solid lines). We use gratings with clearly defined resonances in the infra-red (IR) region (R₁, R₂ and R₃). The dashed lines show the position of resonances of gratings without decorating NPs on them. The Au NPs on a flat Au layer have a resonance in the visible region around 568 nm, however by mounting NPs on gratings, the resonance can be tuned to the IR region by changing the periodicity of gratings. However, the absorption at resonance is relatively low, around 10%.

To boost the absorption in NPs, we propose another nanostructure shown in Fig. 3a. A thin dielectric spacer layer is included between the NPs and Au gratings. Such layers could be a hole or electron transport layer (HTL/ETL) in real PEH devices [7].

![Schematic of nanostructure and absorption in Au NPs with d = 10 nm on Au gratings of L = 260 nm with and without a thin dielectric spacer layer with thickness t = 7 nm](image)

We designed gratings with fixed L = 260 nm and W = 0.2L to have an absorption peak in the visible region. Fig. 3b compares the calculated absorption in three different structures: (1) Au NPs on flat Au layer as a reference (black line); (2) Au NPs on gratings without a spacer layer (blue line); and (3) Au NPs on gratings with a thin spacer layer of t = 7 nm between NPs and gratings (red line). Results show the absorption in Au NPs is enhanced from 24.5% on flat Au, to 40% on Au gratings, to 93% when separated from the gratings by a thin layer.

In the following section, we study the effect of different layer thickness between small Au NPs and flat Au layer in a typical PEH device shown schematically in Fig. 4a. The refractive indices of layer 1 and layer 2 are n = 1.8 and n = 2.5 respectively. The bottom layer is Au acting as the back contact.

![Schematic of nanostructure and absorption in Au NPs with varying dielectric layer thickness, t](image)

Fig. 4b shows absorption in Au NPs for different thicknesses of layer 2 from t = 5-100 nm. Very strong absorption of up to 90% occurs in NPs for t <= 75 nm. Results also show a blue shift of the resonant peak from 730 nm to 660 nm when increasing the thickness from 5 nm to 50 nm. However above t = 50 nm the resonant peak no longer shifts with changing thickness and the absorption is strongly reduced as we increase the t = 75 nm to t = 100 nm. This suggests that the thickness of the layer between NPs and flat Au layer is an important parameter for strong, tunable absorption in Au NPs in the visible spectrum. However, more work is needed to understand the mechanism.

3. Conclusion

We design nanostructures that can enhance and tune the absorption in arrays of small NPs, which have been shown to have more effective hot electron generation. These preliminary designs are a promising method to increase absorption in small NPs and achieve the tunability in absorption spectra for application in high efficiency PEH devices in the future.

References


Low-melting-point borophosphate glass as a matrix for NP-doped, luminescent composites produced using the NPDD method

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Abstract

NanoParticle Direct Doping (NPDD) [1] is a method developed in the Institute of Electronic Materials Technology in Warsaw that allows fabrication of volumetric composites based on glass matrices doped with various kinds of nanoparticles (NPs), including metallic plasmonic NPs, Quantum Dots (QDs) and rare-earth ions. It allows us to obtain photoluminescent (PL) materials co-doped with different types of NPs, varying in size and composition, in which it is possible to observe effects such as plasmonic enhancement of the excitonic emission [1] or radiative energy transfer. [2]

1. Introduction

NPDD method was used to fabricate volumetric composites doped with optically active NPs. As the matrix we have chosen the sodium borophosphate dielectric glass (NBP), which is transparent over wide range of wavelengths, and exhibits melting temperature of ca. 750°C. [3] As optically active elements we have used variety of NPs: CdSe/ZnS core-shell QDs, CdTe QDs, ZnCdSeS QDs, all of them showing luminescence at visible wavelengths, silver NPs showing Localized Surface Plasmon Resonance (LSPR) at 405 nm, and erbium and praseodymium ions.

2. Discussion

We have prepared series of samples with different dopants combination. Absorbance and PL spectra were measured to characterize the materials, as well as time-resolved fluorescence lifetime measurements to study the process of energy transfer between different kinds of NPs. Different approaches of preparing material were tested, including dry mixing of NPs with NBP glass powder and dispersing NPs in toluene during the mixing stage. This modification yielded in improved material homogeneity and increased PL intensity (Fig. 1.).

Figure 1: Absorbance and PL Intensity spectra of NBP glass doped with ZnCdSeS QDs (λ = 530 nm) prepared with and without dispersing QDs in toluene.

3. Conclusions

The versatile of the method can potentially allow to construct a material doped with Ag NPs, QDs and rare-earth ions, especially Pr³⁺ to achieve narrowband Pr luminescence with laser diode excitation at wavelengths that are not absorbed well by the Pr itself. However, quality and homogeneity of composites has to be improved, which can be achieved by modification of the initial powder preparation process.

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References


Optical studies of the Bi$_2$ZnOB$_2$O$_6$ glass doped with silver nanoparticles and Er$^{3+}$ ions

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Abstract
This work reports the optical studies of the Bi$_2$ZnOB$_2$O$_6$ (BZB) glass doped with silver nanoparticles (nAg) and Er$^{3+}$ ions. The material was obtained by modified micropulling down method. LSPR of nAg resonance in BZB glass occurs at 620 nm. Annealing of BZB:nAg:Er$^{3+}$ material at 450 °C caused two fold increase of the luminescence at 1532 nm.

1. Introduction
Laser sources which are used in visible and near infrared mainly are based on glasses doped with rare earth ions. To get high rare earth ion emission the localized surface plasmon resonance (LSPR) can be used. It is possible with co-doping the glass dielectric matrix with therare earth ions and metal nanoparticles [1]. Emission enhancement is associated with the energy coupling of rare earth ions with metallic nanoparticles as a result of energy transfer between LSPR to RE ions.

2. Optical studies
This work reports the optical studies of the Bi$_2$ZnOB$_2$O$_6$ (BZB) glass doped with silver nanoparticles (nAg) and Er$^{3+}$ ions. The use of nAg requires that the matrix temperature should be lower than the melting temperature of the Ag (962°C). BZB glass has a low melting temperature, and due to the presence of heavy metal ions it is likely that the phonon energy will be lower.

The material was obtained by modified micropulling down method in which nanocomposites are produced in the form of rods with a diameter up to 5 mm. This method allows the support of nanoparticles, rare earth ions or quantum dots in the whole bulk material during one process.

Based on absorption measurements, it was found that LSPR of nAg occurs at 620 nm. However the transmission of the BZB decreases when doping level of nAg is higher than 0.3% wt. Also the increase of the Er$^{3+}$ emission form 4113/2 level at wavelength of 1532 nm in doped material was observed. Fluorescence dynamic characteristics show that BZB have high phonon energy.

Additionally the annealing of BZB:nAg:Er$^{3+}$ material at 450 °C caused two fold increase of the luminescence between 4113/2 → 4115/2 levels. This behavior can be associated with lower concentration of OH-hydroxyl groups, which can cause weaker emission of Er$^{3+}$ ions at 1532 nm due to energy transfer from excited state of ion to OH group.

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References
Tunable polaritons enhanced by the spiral nanowire metamaterials

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Abstract

The tunable spiral nanowire metamaterial design at optical frequency is presented, and the surface polaritons are theoretically studied. It was found that the dispersions of the polaritons could be tuned by varying physical dimensions of the spiral nanowire metamaterial. This geometry is unique. Doing so, one may dynamically control the properties of surface polaritons.

1. Introduction

Surface plasmons (SPs) are known as the collective oscillations of the delocalized electrons existing at metal–dielectric interfaces. Owing to their ability to confine light in subwavelength dimensions with high efficiency, SPs offer a route to overcome the diffraction limit of classical optics [1]. Since most of the conventional nanowire metamaterials can be controlled by the limited number of geometrical parameters, the focus of research has been moved to the possibility of tunable SPs by dealing with spiral nanowire metamaterial. Herein, the ability of spiral nanowire metamaterials to support unique absorption resonances related to radiative bulk plasmon-polaritons is theoretically demonstrated. In this work, we develop an effective medium theoretical model for the analytical description of spiral-shaped spoof devices and use it to investigate quantitatively their spectral properties. This model allows for a comprehensive understanding of Ferrell-Berreman (FB) modes supported by the structure.

2. Theoretical model

Herein, we focus on a 2D wire whose surface is decorated by \( n \) spiral-shaped grooves filled with a dielectric material of refractive index \( n_d \). The resulting inner and outer radii, which correspond to the bottom and opening of the grooves, are \( r \) and \( R \), respectively, as shown in Fig. 1(a). The period and width of the grooves along the wire perimeter are \( d \) and \( a \). The spiral is built in such a way that the intersection angle between the tangent to each spiral arm and the radial direction is the same along the spiral length; see Fig. 1(a). These are the so-called logarithmic spirals, characterized by a spiral angle \( \theta \), and can be parametrized as

\[
\begin{align*}
x(t) &= re^{i\cos\theta \cos t} \\
y(t) &= re^{i\cos\theta \sin t}
\end{align*}
\]

In the limit \( a < d \ll \lambda \), a metamaterial approximation, in which the textured PEC is treated a homogeneous effective medium, can be applied. In this homogeneous metamaterial picture, the effective permittivity and permeability in the region between the inner and outer radii acquire a diagonal, spatially independent tensor form. The component of the permittivity normal to the spiral arms (z-direction) is given by \( \varepsilon = \frac{n^2 d}{a} \), while the parallel components diverge. The permeability components are set so that the EM radiation propagates at the speed of light inside the spiral grooves. This procedure yields the following effective permittivity and permeability tensors for TM waves expressed in cylindrical coordinates:

\[
\begin{bmatrix}
\varepsilon^{-1} &= a \\
\mu^{-1} &= \frac{d}{a}
\end{bmatrix}
\]

where the permittivity tensor is restricted to the xy-plane.

![Fig. 1. Localized spoof surface plasmons in a 2D subwavelength PEC wire corrugated with spiral grooves. Cross-section of the corrugated PEC wire with the inner and outer radii \( r \) and \( R \), periodicity \( d \), groove width \( a \), and the spiral angle \( \theta \) (a); Schematic view of a nanowire composite (b).](image)
3. Modelling and the analytical solution

The proposed geometry of the nanowire composites is shown in Fig. 1(b). Nanowires with permittivity \( \varepsilon_m^M \) are embedded in a dielectric host material with permittivity \( \varepsilon_d^M = 2.4 \). On the basis of an effective medium approximation we evaluate the effective permittivities of the nanowire metamaterial according to:

\[
\varepsilon_{\perp}^M = \varepsilon_d^M \left[ \frac{\varepsilon_d^M (1 + \rho^M) + \varepsilon_m^M (1 - \rho^M)}{\varepsilon_d^M (1 - \rho^M) + \varepsilon_m^M (1 + \rho^M)} \right] \quad (5)
\]

\[
\varepsilon_{\parallel}^M = \varepsilon_m^M \rho^M + \varepsilon_d^M \left( 1 - \rho^M \right) \quad (6)
\]

Here, subindex M refers to the metamaterial medium, and \( \rho^M \) is the metal filling fraction ratio which is defined as:

\[
\rho^M = \frac{\text{nanowire area}}{\text{unit cell area}} \quad (7)
\]

To explore and demonstrate the properties of surface waves we adopt a Drude model to characterize the metal (i.e. silver), expressing the permittivity as \( \varepsilon_m^M (\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\sigma\omega}. \)

The parameters are obtained by fitting this permittivity function to a particular frequency range of bulk material. It is found [2] that for silver, the values of \( \varepsilon_\infty = 5 \), \( \omega_p = 2.2971 \times 10^{15} \text{ Hz} \), \( \sigma = 2.3866 \times 10^{13} \text{ Hz} \) give a reasonable fit. We calculate the metal filling fraction \( \rho^M \) based on the values of the pore diameter \( \left( d^M \right) \) and spacing \( \left( S^M \right) \) and, assuming a perfect rectangular structure, we apply the following equation:

\[
\rho^M = \frac{\pi \left( d^M \right)^2}{4 \left( S^M \right)^2} \quad (8)
\]

Fig. 2. The dependences of the dispersion relations of surface polaritons on corrugated wire periodicity \( d \).

With this assumption it is possible to derive a dispersion relation for the surface modes localized at the interface between metamaterial and PbS. Evaluating the tangential components of the electric and magnetic fields at the interface it is then, in turn, possible to obtain a single surface mode with the propagation constant \[ \beta = k \left( \frac{(\varepsilon_{\text{PbS}} - \varepsilon_\parallel^M)\varepsilon_{\text{PbS}}\varepsilon_{\perp}^M}{\varepsilon_{\text{PbS}}^2 - \varepsilon_{\parallel}^M \varepsilon_\parallel^M} \right)^{1/2} \quad (9) \]

where \( k \) is the wavenumber (absolute value of the wavevector in vacuum) and \( \beta \) is the component of the wavevector parallel to the interface. By substituting effective permittivity in different direction from Eq. (3) in Eqs. (5), (6) we arrive at the effective permittivities of the spiral nanowire metamaterial as follows:

\[
\varepsilon_{\perp}^{SM} = -\varepsilon_d^M \left( \rho^M - 1 \right) - \frac{ad\varepsilon_m^M \sin(2\theta)(\rho + 1)}{2} \quad (10)
\]

\[
\varepsilon_{\parallel}^{SM} = -\varepsilon_d^M \left( \rho^M - 1 \right) - \frac{ad\varepsilon_m^M \rho^M \cos(2\theta) + 1}{2} \quad (11)
\]

In conclusion, we have theoretically studied the electromagnetic properties of spiral nanowire metamaterials based on the permittivity homogenization model. Developed theoretical model allows to design and investigate spoof plasmon devices with spiral textures in the optical frequency range. The future works include enhancement of the existing model by replacing silver nanowires with the graphene analog.

**References**


Purcell enhancement and photoluminescence spectra shift of the APbI₃ (A=Cs, FA) Perovskite nanocrystals coupled to Hyperbolic Metamaterials

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Abstract
In this paper, hyperbolic metamaterials (HMM) are properly designed, simulated and fabricated as an outstanding photonic structure able to control the emission rate of lead halide perovskite nanocrystals (PNCs) deposited on the top. Geometrical parameters (thicknesses of the metal and the dielectrics layer) are optimized to enhance coupling between the HMM and the exciton confined in the PNCs. The device is tested for two different PNCs, CsPbI₃ and FAPbI₃, and demonstrate an increase of the exciton radiative recombination rate by more than a factor of 2-3 together with the red shift of the emission spectra.

In the wide range of photonic applications, controlling the spontaneous emission rate of a given active material is a requisite parameter to develop more complex devices as single-photon emitters, lasers, or amplifiers. From one side, nanofabrication techniques have enabled the development of thin (~10 nm) multilayer structures alternating metals and dielectrics (see Figure 1a). The right choice of the thickness and periodicity results in an outstanding type of Bragg mirror called hyperbolic metamaterial (HMMs) [1]. Since HMMs structures present the peculiar ability to manipulate the near field of a quantum emitter (QE) in a given direction [2], they have rapidly gained a key role in nanophotonics. In particular, the coupling of light emitters to the HMM structure is expected to improve the exciton radiative recombination rate by a Purcell effect mechanism, [3] whose efficiency can be engineered by controlling the distance between a QE and the HMM structure. On the other hand, lead halide perovskites nanocrystals have emerged as promising materials for developing high-quality optoelectronic devices under cheap, straightforward, and low-temperature technologies [4]. In this work, we propose the manipulation of photons produced by exciton radiative recombination in CsPbI₃ and FAPbI₃ PNCs employing HMM structures. The exciton-HMM coupling will lead to the enhanced spontaneous emission by a factor greater than three in CsPbI₃ and around factor two in FAPbI₃ PNCs with the thinnest space, together with a photoluminescence redshift of around 10 nm.

Discussion
The HMM structure used in this work consisted of six periods of alternating metal (Ag) and dielectric (LiF) layers and finished with the metal (Ag), as illustrated in Fig. 1a. The average thickness of Ag + LiF layers is around 25 ± 35 nm. The coupling between excitons in CsPbI₃ and FAPbI₃ PNCs with the HMM modes is controlled by a variable dielectric spacer thickness (investigated in the range of 10–50 nm). The spacer is made of poly (methyl methacrylate) (PMMA) spin-coated on the HMM structure at 3000 rpm. Finally, on top of the PMMA spacer layer, CsPbI₃ and FAPbI₃ PNCs were deposited by dip coating the substrate into the colloidal solution. For low-temperature photoluminescence (PL) and time-resolved PL (TRPL) measurements, the samples were held in the cold finger of a closed-cycle He cryostat, which can be cooled down to 15
K, approximately. (for more details see Ref. [1]). The exciton-HMM coupling in our system leads to the Purcell-enhanced spontaneous emission by a factor greater than three in CsPbI3 and around 2 in FAPbI3 PNCs with the thinnest spacer. In particular, four samples were fabricated with nominal spacer thicknesses \(d = 10, 20, 50,\) and \(250\) nm; the thickest one (250 nm) was considered here as a reference because the exciton-HMM coupling is expected to be negligible in this case. It is worth noting that we observe an insignificant effect of the HMM structure on the PL decay kinetics of PNCs at room temperature due to the low PL quantum yield at these conditions [5], whereas at 15 K the same sample demonstrated a clear reduction of the PL decay time. Accordingly, we implemented our study at low temperatures to observe the Purcell effect at optimum conditions.

The reduction of the spacer thickness down to \(d = 10\) nm showed resulted in the emitted PL redshift (\(\Delta \lambda\)), as illustrated in Fig. 2a and 2b for CsPbI3 (\(\Delta \lambda = 8\) nm) and FAPbI3 (\(\Delta \lambda = 10\) nm) nanocrystals, respectively. Since this redshift is correlated with the shortening of the lifetime observed in Figs. 2c-d, it is attributed to an effective Purcell effect resulted from the coupling of perovskite emitters to the HMM modes.

Figure 2: PL spectra (a,b) and PL decay kinetics (c,d) of FAPbI3 and CsPbI3 PNCs, respectively, deposited on top of HMM substrates for different spacer thicknesses. Measurements were performed at 15 K.

Figure 3 illustrates the normalized spatial distribution of the absolute value of the electric field of a point source dipole, with the polarization parallel (Fig. 3a–c) and perpendicular (Fig. 3b–d) to the multilayer stacks, when it is located at the top surface of the thinnest (Fig. 3a–b corresponding to \(d = 10\) nm) and thickest (Fig. 3c–d corresponding to \(d = 250\) nm) spacers. To show the propagation of the energy flux, we plotted the Poynting vectors in logarithmic scale within the plane where the dipole oscillates. The electric field is spatially expanded into the metal-dielectric multilayer for both dipole polarization when the dipole gets close to the HMM structure (10 nm). The power dissipated down to the HMM structure is the key physics to understand the observed increase of the spontaneous emission rate of the emitters. On the contrary, for a very thick spacer, the point dipole is very far from the multilayer, and its interaction with the metal-dielectric multilayer is substantially reduced, as observed experimentally.

### Conclusion

To summarize, we investigated an enhancement of the rate of spontaneous emission of CsPbI3 and FAPbI3 PNCs using HMM structures. The coupling of excitons photogenerated in two different PNCs to the optical modes of these HMM substrates induces a Purcell factor by more than three in CsPbI3 and around two in FAPbI3 nanocrystals, and also the redshift of the emitted PL. The thickness of the spacer allows to engineer exciton-HMM coupling. We believe that the proposed device has potential applications in the implementation of single-photon emitters for quantum communications and computing, among other applications.

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### References


Influence of primary beam energy on localized surface plasmon resonances mapping by STEM-EELS

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Abstract

We present an experimental study of the influence of primary beam energy on localized surface plasmon resonances mapping by scanning transmission electron microscopy combined with electron energy loss spectroscopy. The best results are obtained using a medium primary beam energy (120 keV) as the primary beam energy should be high enough to suppress the scattering in the sample and at the same time should be low enough to avoid the appearance of relativistic effects.

1. Introduction

Localized surface plasmon resonances (LSPR) are self-sustained collective oscillations of free electrons in metal nano- and microstructures. Mapping of LSPR with high spatial and energy resolution is necessary to understand their origin and properties. Scanning transmission electron microscopy (STEM) combined with electron energy loss spectroscopy (EELS) has become a standard technique to map LSPR with a nanometer spatial and 10 meV to 100 meV energy resolution. In EELS, a swift electron propagating with a certain velocity loses a tiny part of its kinetic energy by performing work against the electric field produced by itself. Consequently, the loss probability measured by EELS is related to the induced electric field parallel with the electron beam.

We have experimentally studied the influence of the primary beam energy and the collection semi-angle on the localized surface plasmon resonances measurement by STEM-EELS to make an instructive overview for the beginners in the field [1] which was missing as there has been no experimental work discussing the experimental conditions during the measurement.

2. Results and discussion

We have discussed the impact on experimental characteristics which are important to detect localized surface plasmon peaks in EELS successfully, namely: the intensity of plasmonic signal, the signal to background ratio, and the signal to zero-loss peak ratio considering a limited dynamic range of the spectrometer camera [1]. The plasmonic object of our interest were gold nanorods (240 nm × 80 nm × 30 nm) fabricated by focused ion beam milling [2] of a 30 nm thick polycrystalline gold layer deposited on 30 nm thick silicon nitride membrane. We note that nanorods manufactured from the polycrystalline layer have a similar plasmonic quality as nanorods manufactured from the monocrystalline gold platelets [3].

We took a series of 3 rods and do the STEM-EELS measurement at the primary beam energy of 300 keV, 120 keV, and 60 keV. Figure 1(a) shows EEL spectra of one rod recorded at different beam energies. We clearly see that the signal corresponding to the LSPR is the strongest for the 60 keV electron beam and the weakest for the 300 keV electron beam. Moreover, if we consider the second peak in experimental EEL spectra in Figure 1(a) at 1.76 eV corresponding to the longitudinal quadrupole mode, we see that lower beam energies are better for observation of weaker plasmon modes. If we consider measured raw EEL spectra in Figure 1(a), we clearly see that the peak at 1.08 eV corresponding to the longitudinal dipole mode is the most noticeable when using 120 keV electron beam. In the case of 300 keV electron beam the background is enhanced by relativistic effects like the Cerenkov radiation as the speed of the 300 keV electron is higher than the speed of the light in the silicon nitride membrane [4] with the refractive index around 2. On the other hand, the raw EEL spectra measured with a 60 keV electron beam has the highest background in the lower energy loss region. This is caused by a higher probability of all scattering events as the mean free path of slower electrons in the sample is smaller. Focusing on EEL maps in Figure 2(a) we easily see that the EEL maps recorded at 60 keV are rather noisy and the spatial distribution of the LSPR seems to be more confined when measuring with lower beam energies. However, inspecting the line profiles in Figure 2(b) we clearly see that the spatial distribution of the LSPR is similar for all three primary beam energies. Consequently, the only difference in the EEL maps is in the signal to noise ratio. Therefore, the optimal primary beam energy should be high enough to measure the signal at positions in the metal with a good signal to noise ratio.

3. Conclusions

The best results in terms of the best signal-to-background ratio are obtained using a medium primary beam energy as the primary beam energy should be high enough to suppress
Figure 1: EEL spectra of the same rod at different beam energies: (a) measured raw EEL spectra and extracted signal; (b-d) STEM annular dark field (ADF) images of the rod with marked area for integration of EEL spectra in (a) recorded during STEM-EELS mapping at 300 keV (b), 120 keV (c), and 60 keV (d); (e) signal-to-background ratio for the longitudinal dipole (green) and quadrupole mode (red).

Figure 2: (a) Maps measured by EELS: relative thickness of the gold nanorod and EEL maps of the longitudinal dipole mode at 1.08 eV and the longitudinal quadrupole mode at 1.76 eV recorded at different primary beam energies (300 keV, 120 keV, and 60 keV). (b) Line profiles of the EEL maps of the longitudinal dipole mode along the dashed black lines in (a). The zero position corresponds to the middle of the rod.

References


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Resonance-order dependent PIT in orthogonally arranged nanoscale cavities

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Abstract

We investigate the Plasmonic Induced Transparency (PIT) in a resonator structure consisting of two orthogonally arranged metal-insulator-metal (MIM) nanocavities by FDTD simulation and a classical mechanical model. The model calculations show the PIT caused in the orthogonally arranged cavities possesses a clear resonance order dependence. These results demonstrate the order selective spectrum modulation effect in nanoscale resonator structures.

1. Introduction

Metamaterials consist of subwavelength resonance nanostructures have brought us significant advances in light manipulation techniques. The extraordinary optical properties of the metamaterial arise as the dispersive property near the resonance frequency of individual nanostructure: meta-atom. Therefore, investigations of the resonance spectrum of the meta-atoms are indispensable for designing and making the metamaterials.

One of the phenomena that can significantly modulate the spectral shape near the resonant frequency of the resonator is the electromagnetically induced transparency (EIT)-like effect, named plasmonic induced transparency (PIT) [1-3]. The EIT is a quantum phenomenon that arises from interference between different excitation pathways in a three-level atomic system. The PIT, a plasmonic analog of the EIT, occurs due to interference between plasmonic structures, such as metal rods and cavities. The PIT, which enables significant manipulation of the dispersive properties by coupling resonances between cavities, has been applied in various fields, such as sensing devices [4] and waveguide systems [5].

In this work, we investigate the resonance interaction between the two types of MIM cavities that constitute the orthogonally arranged resonator structure [6,7]. A FDTD simulation reveals that the PIT phenomenon occurred when both cavities exhibited the first-order resonance at the same resonance frequency. However, the PIT phenomenon disappeared when one of the cavities exhibited second-order resonance. We also model the resonance order dependence of the PIT effect in this orthogonally arranged resonator by using the classical mechanical analog of PIT.

2. Results

![Figure 1: Schematic of multi-layered structures used for FDTD simulations. (a) Orthogonally arranged resonator structure and components. (b) The whole simulation area.](image)

Figure 1 (a) shows a schematic of the resonator structure constructed by two different types of MIM cavities studied in this work. We put the Au block with a height of 100 nm on a Au/Al$_2$O$_3$ layer to form the open-ended cavity (hereinafter called “open cavity”). A narrow slit with a depth $d$ ranging from 0 to 100 nm was incised in the upper Au block to form the closed cavity (“closed cavity”). A Au ridge as a coupler for launching SPP WPs was placed on the same surface, as shown in Fig. 1 (b). Time evolutions of the vertical component of electric fields ($E_y(t)$) were recorded at a point $P$, located at the right edge of the resonator structure and the center of the Al$_2$O$_3$ layer. We also prepared the reference model, which had an identical construction except for removing the resonator structure. We evaluated the resonant spectrum of the compound resonator, $R(\omega)$, as

$$R(\omega) = \frac{|F_{res}(\omega)|^2}{|F_{ref}(\omega)|^2},$$

where $F_{res}(\omega)$ and $F_{ref}(\omega)$ were the spectra calculated by the fast Fourier transform (FFT) of the $E_y(t)$ measured at point $P$ in the resonator model and reference model, respectively.

Figure 2 (a) shows typical resonance spectra obtained for several slit depths $d$ in the closed cavity. The original open cavity ($L = 100$ nm) was prepared for having the first-order resonance at a wavelength near 1000 nm. The two-dimensional plot of the resonance spectra as a function of the wavelength and $d$ shown in Fig. 2 (b) more clearly shows the slit depth dependence of resonance spectra. Dashed white
3. Discussion

First, we start with a system consisting of two magnetic dipoles $P_C$ and $P_0$ representing the closed and open cavities as a model for the case when the two cavities both exhibit the first-order resonance. The dynamic equation of the system can be described as a linearly coupled Lorentzian oscillators as follow [2]:

$$\begin{align*}
\frac{P_C}{P_0} & = \left( \begin{array}{cc}
\omega_0^2 - \omega^2 - i\gamma_0\omega & -\Omega^2 \\
-\Omega^2 & \omega_0^2 - \omega^2 - i\gamma_0\omega
\end{array} \right)^{-1} \times \left( \begin{array}{c}
0 \\
g_1 E_0
\end{array} \right),
\end{align*}$$

where $\omega_0$ and $\omega_0$ are the resonant frequencies, $\gamma_C$ and $\gamma_0$ are the damping constant of the dipoles, $g_1$ is the coupling constant between the $P_0$ and the incident field, and $\Omega$ is the coupling constant between the two dipoles. For a simplicity model, we assumed the closed cavity decoupled from the external fields.

In addition to the first model, we construct a system consisting of two dipoles that represent the open cavity ($P_{0_1}$, $P_{0_2}$) and one dipole that represent the closed cavity ($P_C$) as a model when the open cavity exhibits the second-order resonance ("second-order model"). Similar to Eq. (2), the dynamic equations follow [2,3]:

$$\begin{align*}
\frac{P_C}{P_{0_1}} & = \left( \begin{array}{cc}
\omega_0^2 - \omega^2 - i\gamma_C\omega & -\Omega^2 \\
-\Omega^2 & \omega_0^2 - \omega^2 - i\gamma_C\omega
\end{array} \right)^{-1} \\
0 & \times \left( \begin{array}{c}
0 \\
g_2 E_0
\end{array} \right),
\end{align*}$$

Here, we set the coupling constants $g_2$ of the $P_{02}$ with the incident field as $g_2 = -g_1$ to represent the $\pi$-phase shift between the two magnetic oscillations in the second-order resonance. The parameters were as follows: $\omega_0 = 300 \text{THz}, y_C = y_0 = 25, \Omega = 120, g_1 = -g_2 = 1, E_0 = 1$.

Based on Eq. (2) and (3), we can obtain the susceptility of the dipole response, $\chi_0 = P_0/E_0$ and $\chi_{0_1} = P_{0_1}/E_0$.

Figure 3 shows the imaginary parts of the $\chi_0(\omega)$ and $\chi_{0_1}(\omega)$ representing the energy dissipation. The results of the two models shown in Fig. 3 indicates a similar trend to the FDTD simulation. In Fig. 3(b), the two oscillators couple and show a splitting into two modes due to the PIT, whereas in Fig. 3(d), the resonance spectrum is invariant to the $P_C$ because the $P_C$ is not coupled to the $P_{0_1}$ and $P_{0_2}$.

4. Conclusions

In conclusion, we numerically demonstrated the PIT phenomenon in the orthogonally arranged nanoscale resonator. In this resonator, significant modulation of resonance spectra due to the PIT phenomenon strongly depends on the resonance order of one of the two cavities. The order-selective PIT phenomenon observed in this study can be used to manipulate the resonance spectrum of the cavity, such as adjusting the exact spectral shape or suppression of resonances of a specific order.

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References

The suitability of a terahertz near-field microscope to quantitatively determine the conductivity and the charge carrier density of semiconductors is explored. For doped and optically excited silicon, the charge carrier density is successfully extracted from the relative phase of the terahertz near-field signals. This technology is promising for non-contact and nanoscale-resolved characterization of electronic devices and materials.

1. Introduction s-SNOM

Scattering-type Scanning Near-field Optical Microscopy (s-SNOM) is a near-field imaging and spectroscopy technique which can overcome the classical diffraction limit of light and offers nanometer spatial resolution independent from the used wavelength [1]. It is based on an Atomic Force Microscope (AFM), whose cantilever tip is illuminated by electromagnetic radiation at the desired frequency (see Fig. 1). The near-field interaction between the tip apex and the sample leads to scattering of radiation with a strength and relative phase which contain information about the local dielectric function of the sample.

The response of an electron-hole plasma in a semiconductor to an electromagnetic excitation can in many cases be described by the Drude model. A key quantity is the characteristic angular plasma frequency \( \omega_p \) which scales with the square root of the charge carrier density \( n \) according to

\[
\omega_p = \sqrt{\frac{n e^2}{m^* \varepsilon_0}}.
\]

It is well-known, that s-SNOM can probe the Drude behavior and allows to visualize differences in the conductivity (e.g., caused by different doping levels) on the nanoscale. This has been demonstrated in the literature using continuous-wave and pulsed THz sources [3, 4, 5]. Here, we extend this work and focus on the quantitative determination of the conductivity, respectively the density \( n \), using an electronic CW radiation source at a single frequency.

In Fig. 2, the s-SNOM signal (amplitude and phase) expected for bulk Si probed at three different THz wavelengths (0.2, 1.0 and 5.0 THz) is displayed as a function of the charge carrier density \( n \). The simulation is based on the dipole model of Ref. [6], and assumes a momentum scattering time \( \tau \) of 200 fs, an effective carrier mass \( m^* = 0.26 m_e \), and a negligible thickness of the oxide layer on top of the Si specimen. For charge carrier densities far away from the plasma frequency, the s-SNOM signal is constant, but close to it, there are strong signal contrasts in both amplitude and phase. The key idea of our work is to properly select the radiation wavelength for the expected density range and to exploit the relative phase, which can be measured readily in absolute terms, to determine the carrier conductivity and density \( n \).

3. Charge carrier density measurements

We demonstrate the quantitative determination of the charge carrier density in Si samples for two types of sam-
conductivity model, and taking into account the specifics of photo-excitation, carrier diffusion and Auger recombination in Si, we are able to numerically fit the s-SNOM data and extract the conductivity, and – with the knowledge of \( \tau \) – the charge carrier density.

### 3.2. Impurity-doped Si

In a second experiment, we test the accuracy of the determination of the charge carrier density by a single-frequency measurement on a boron-doped Si specimen (without optical excitation). The phase of the THz near-field signal is referenced against that measured with a gold surface. The extracted charge carrier density compares well with the manufacturer’s specification.

### 4. Conclusions

We have demonstrated the ability of s-SNOM to quantitatively determine the conductivity and the charge carrier density of optically excited or impurity-doped bulk silicon. Even a measurement at a single well-chosen frequency can be sufficient to derive absolute values from the relative phase of the s-SNOM signal.

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### References


Surface plasmon-assisted spin precession in Au/YIG heterostructures

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Abstract
We report amplification of laser-induced spin precession in Co-doped YIG employing a surface plasmon excitation in a metal-dielectric magneto-plasmonic crystal. Our results are important for non-thermal control of all-optical magnetization reversal in dielectrics and its nanoscale localization.

1. Introduction
A rapidly developing branch of modern nanophotonics, magneto-plasmonics has a potential for unraveling a plethora of novel mechanisms of the light-matter interaction in metal-dielectric heterostructures. Recently we have elucidated the role of surface plasmon-polaritons (SPPs) in localized Inverse Faraday effect [1] and superdiffusive electron transport [2]. In this work, we employ this magneto-plasmonic approach for amplifying the photo-magnetic spin precession in dielectric Co-doped yttrium iron garnet (YIG:Co). We observe substantial increase of the magnetization precession amplitude at the SPP resonance. Our results represent an important step towards the nanoscale photomagnetic effective data recording by femtosecond laser pulses.

2. Experimental details
The experimental setup is shown in Figure 1a. 8 micron-thick YIG:Co film was covered with a 50 nm-thick Au grating with a period of 800 nm to enable the SPP resonance. The SPP excitation in Au/YIG:Co magneto-plasmonic crystals was performed by linearly polarized 50 fs pump pulses. The pump wavelength was varied from 1200 to 1350 nm. The delayed 50 fs, 800 nm probe pulses were employed for monitoring the spin precession in the YIG:Co film through transient Faraday rotation. Both pump and probe pulses were P-polarized. The measurements were performed at a magnetic field of 3.2 kOe directed in the plane of the sample. For each wavelength, measurements were done at the two opposite directions of the magnetic field in order to remove non-magnetic effects. We observe an enhancement of the magnetization precession at the SPP resonance (Fig. 1b).

3. Discussion
Employing the Lumerical FDTD software package, we calculated the effective depth of the photo-magnetic excitation (Fig. 2a) and its specific efficiency (Fig. 2b). In a bare YIG:Co film, the photomagnetic effect is responsible for...
for the excitation of large-amplitude spin precession with a frequency of about 5 GHz corresponding to the ferromagnetic resonance mode [3]. However, when the pump beam is coupled to the surface plasmon resonance, the increase of the precession amplitude was observed in the 300 nm active layer, comparing to the bare YIG:Co. It is seen that the resonant SPP excitation leads to a 6-fold amplification of the specific amplitude of the magnetization precession.

![Figure 2: Calculated effective depth of the photo-magnetic excitation (a). Specific efficiency of the photo-magnetic excitation for the bare garnet (open dots) and Au:YIG/Co (full red dots). The solid red line is the result of the numerical simulations.](image)

4. Conclusions

We have shown plasmon-assisted control of the spin precession amplitude in YIG:Co thin films covered with a 50 nm-thick Au grating. Our results demonstrate the concept of amplification of angle of photo-magnetic precession via SPP resonance in dielectric YIG:Co films spatial localization below diffraction limit. Increasing the

amplitude of magnetic precession without additional energy consumption is a promising solution for more efficient ultrafast information recording.

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References

Towards perfect metallic behavior in optical resonant absorbing nanostructures

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Abstract

Looking for a perfect metallic behavior is a crucial research line for metamaterials scientists. We propose a versatile strategy based on a contrast of dielectric index to control dissipative losses in metals within waveguides and resonant nanostructures. This permits to tune the quality factor of the guided mode and of the resonant absorption over at least four orders of magnitude. This concept is applied to a practical design that permits to finely control the localization of dissipation in an absorbing photonic structure.

1. Introduction

Metals are essential building blocks of photonic architectures notably because of their high negative permittivity. But metals are also lossy and this triggered the development of many strategies to reduce or at least control these losses [1, 2, 3, 4, 5]. Promising studies even show that it is possible to completely get rid of dissipative losses and reproduce many metamaterial concepts initially based on metals by using only dielectrics [6]. But for some applications, especially when involving absorption, a fine control of dissipative losses is preferable to a complete removal. To address this issue, we propose to improve noble metals performances by integrating them within an architecture of optical resonant nanostructure whose loss rate can be tuned over several orders of magnitude.

2. Three-dielectric architecture

Our approach consists in replacing the dielectric core of a metallic waveguide by several layers of different optical indices chosen to concentrate the field within the middle of the guide. Its penetration in the metallic parts is thus limited, which results in a lower mode loss rate. As depicted on Fig. 1(a), we propose a symmetric three-dielectric architecture composed of a high index layer \(n_2 = 4.0\) placed between two low index layers \(n_1 = 1.4\) and surrounded by gold metallic walls. The fill factor \(f\) designates the proportion of high index dielectric to a complete removal. To address this issue, we propose to improve noble metals performances by integrating them within an architecture of optical resonant nanostructure whose loss rate can be tuned over several orders of magnitude.

As this strategy is particularly adapted to guided modes, we consider waveguide architectures to highlight the potential of this approach on a simple model before applying it to a photonic resonator. For both cases, the quality factors of the structures get boosted by a factor of at least \(10^3\). To illustrate the applicability of this approach, a design of a photonic absorber where the incoming radiation gets absorbed in a very thin layer, i.e., \(10\) nm, is proposed.

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Figure 1: Proposed three-dielectric architecture. \(n_1\) and \(n_2\) are set to 1.4 and 4.0. Wavelength in vacuum \(\lambda\) and guide width \(h\) are respectively set to 4.0 \(\mu m\) and 2.0 \(\mu m\). Permittivity of gold is obtained with a Drude model of parameter \(\gamma = 0.048\) and \(\omega_p = 1.2 \times 10^{16}\) s\(^{-1}\) [7]. Gold walls are considered semi-infinite. (a) Schematic view of the proposed waveguide structure. (b) Form of the normalized magnetic field \(H_y\) of the TM\(_{0}\) mode for various values of fill factor \(f\). (c) Dependency on \(f\) of the waveguide mode TM\(_{0}\) quality factor \(Q\), defined as \(\beta / 2\beta''\), where \(\beta = \beta' + j\beta''\) is the propagation constant of the mode. (d) Schematic view of the guided-mode resonator (GMR) based on this architecture and absorption spectrum of two structures: (i) \(f = 0\) guide, \(p = 2.94\) \(\mu m\), \(L = 460\) \(nm\). (ii) \(f = 0.5\) guide, \(p = 1.14\) \(\mu m\), \(L = 160\) \(nm\).
The one-dielectric cases \( f = 0 \) and \( f = 1 \) exhibit slightly different forms of the field within the core but a very similar penetration in the metallic walls, whereas choosing an intermediate value for \( f \) indeed permits a confinement of the field and a limited penetration. Figure 1(c) shows the evolution of the Q-factor as a function of fill factor. The resulting curve suggests that multi-dielectric guides allow to finely tune the quality factor and reach values more than three orders of magnitude higher than those of one-dielectric guides. For the considered guide width and wavelength \( \hbar = 2 \mu m, \lambda = 4 \mu m \), the best results are obtained for \( f = 0.5 \).

Figure 1(d) presents the adaptation of this waveguide architecture to a photonic absorber: a guided mode resonator (GMR). Under illumination, this structure resonates when a grating-diffracted order coherently couples with a guided mode. When perfect impedance matching is obtained between free-space and the TM\(_0\) mode of the three-dielectric waveguide, the quality factor of the GMR resonant absorption peak is directly related to the quality factor of the mode. As a consequence, this offers the possibility of spectrally very narrow photonic absorber. Figure 1(d) compares a one-dielectric and a three-dielectric GMR to highlight a 10\(^3\) gain on the peak quality factor. Moreover changing fill factor \( f \) as well as guide width \( h \) permit to finely tune \( Q \) over at least 4 orders of magnitude.

3. Control of the absorption

A promising application of this general concept is to adapt the GMR architecture to concentrate all absorption in a thin active layer. Figure 2 portrays the introduction of such a layer at the center of the dielectric core within the considered three-dielectric design (Fig. 2(a)) and a conventional one-dielectric GMR architecture for reference (Fig. 2(b)).

Adding this active layer to the conventional one-dielectric GMR does not affect much its response. Only 6% gets absorbed within the layer. As for the three-dielectric architecture, this important new source of losses drastically reduces the quality factor of the peak \((6.7 \times 10^4 \text{ against } 640)\). However, nearly all the absorption now occurs in this active layer: 97% for the proposed design.

References


Optical Rectification in Meta-Gratings with Broken Inversion Symmetry

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Abstract

We report on optical rectification effect generated by infrared absorption and diffraction in a periodic 1D meta-grating with a broken inversion symmetry in its unit cell. The photon-drag enabled effect in this case is substantially enhanced by surface plasmon polaritons, resulting in infrared driven ratchet transport of electrons.

1. Introduction

Optical Rectification (OR) refers to the process of generation of DC electric voltage or current in a sample irradiated with light. It is a consequence of atomic or molecular polarization or unidirectional momentum transfer from the light wave to free electrons. In conductive materials, it is frequently termed as photon drag. In a meta-grating, the process can be enhanced by the excitation of Surface Plasmon Polariton (SPP) waves, which is typically realized by using subwavelength metal films with a periodically patterned surface that absorbs and diffracts the incident light [1,2]. Note that the net displacement of electrons in one direction driven by oscillating electric field is only possible in the systems with broken inversion symmetry. It can be induced either by an oblique incidence of the laser beam onto the sample, or by creating asymmetric unit cell in a meta-grating. The latter method was first demonstrated in [2] and is deployed here with a substantially greater 4x efficiency.

Another closely related approach relies on a ratchet effect in periodically modulated samples, where the inversion symmetry is broken by a phase shift between the excited SPP wave and the periodically modulated electron density [3]. A similar effect has been investigated in the THz frequency range using graphene samples [4]. Our work aims at a realization of the ratchet effect in the infrared domain, providing a base on which potential extensions to frequency up- and down-conversion can be built, along with ultrahigh-speed detection in parallel by direct conversion of a fraction of the electromagnetic to voltage readout.

2. Experiment

The 1D meta-grating sample was produced by electron-beam lithography. The grating is formed by 80 nm thick Au slabs on top of a 100 nm thick continuous Au film on a glass substrate. An SEM image of the grating is shown in Figure 1 b) and the cross-section view of the grating unit cell is sketched in Figure 1 a). The meta-grating consists of 100 unit cells with a period \(D = 1.5 \, \mu m\) and a transversal dimension of 100 \(\mu m\). The non-symmetric unit cell is formed by two slabs of unequal widths: \(A_1 = D/2\) and \(A_2 = D/5\), separated by groves with widths: \(B_1 = D/5\) and \(B_2 = D/10\). The underlying gold film is electrically connected to a lock-in amplifier for the OR current measurements (input impedance 1 k\(\Omega\)).

Figure 1: A sketch (a) and an SEM image (b) of a 1D grating with a non-symmetric unit cell used in the experiment.

Figure 2: Experimental optical rectification data. a) OR signal at normal incidence, plotted vs. the laser polarization angle \(\alpha\). b) OR signal at \(\alpha = 90^\circ\), plotted vs. the angle of incidence \(\theta\).
The sample is illuminated by a linearly polarized cw diode laser at \( \lambda_{\text{Las}} = 808 \) nm, focused to a spot with a diameter (FWHM) of 120 μm. The mean laser power incident on the grating area is 50 mW. The laser beam is on-off modulated by a mechanical chopper and the OR signal is detected at the modulation frequency.

Figure 2 a) shows the detected OR signal at normal incidence, plotted vs. the angle \( \alpha \) between the direction of the grating grooves and the laser polarization. The signal is maximized at \( \alpha = \pm 90^\circ \), when the laser radiation most effectively drives the electrons oscillations across the grating structure and excites the SPP wave propagating along the film. The maximal OR current reached 4 nA that corresponds to the efficiency of 12 mV per MW/cm². Our result is thus 4 times higher than that reported earlier [2] in which a nanosecond pulsed laser with a much higher instantaneous power and a grating with a larger area: 600 μm × 600 μm were used.

Figure 2 b) shows the OR signal dependence on the angle of incidence, with a maximum signal at \( 0^\circ \) and a clear angular asymmetry, as one might have expected.

### 3. Discussion

The findings can be understood by considering diffraction of the laser light from the non-symmetric grating shown in Figure 1. The intensities of diffraction orders \( m = 0, \pm 1, \pm 2, \pm 3 \) were calculated with the help of COMSOL and are plotted in Figure 3 vs. the angle of incidence. The non-symmetric profile of the grating leads to unequal intensities of positive and negative diffraction orders. The grating was designed to maximize the difference between the orders \( m = \pm 1 \) and \( m = \pm 2 \) for \( \lambda_{\text{Las}} = 808 \) nm at normal incidence, corresponding to maximum momentum transfer to the grating. Note also the peaks in \( m = \pm 1 \) and \( \pm 2 \) at \( \theta \approx \pm 32^\circ \). These peaks lead to the peaks in the OR signal that can be seen in Figure 2 b) at \( \theta \approx \pm 35^\circ \).

A different picture appears when one considers the conditions for the SPP excitation. Diffraction of light on the grating structure leads to the excitation of SPP under a condition:

\[
K_{\text{SPP}}(\omega_{\text{Las}}) = k_{\text{Las}} \sin \theta + mq
\]

Where \( K_{\text{SPP}}(\omega_{\text{Las}}) \) is the wave vector of SPP at the laser frequency, \( k_{\text{Las}} \) is the laser wave vector, and \( q \) is that of the grating. Since \( K_{\text{SPP}}(\omega_{\text{Las}}) \) is always larger than \( k_{\text{Las}} \), the grating is required in order to fulfill the momentum conservation. At a normal incidence this leads to \( mq = K_{\text{SPP}}(> k_{\text{Las}}) \) and the corresponding diffraction order \( m \) propagates as an evanescent wave along the grating surface. Earlier work [2] used the grating with a period slightly exceeding the laser wavelength, where the first order diffraction may lead to SPP excitation. In the present work, we have designed a grating with a period, approximately twice the SPP wavelength. The condition (1) is thus fulfilled by setting \( 0 \approx 0, m = \pm 2 \) and the SPP is excited by transferring two units of the grating momentum. As one can see in Figure 3, this is realized close to the normal incidence, \( \theta \approx 4^\circ \), where the intensity of reflected \( m = 2 \) beam rises from zero to \( \approx 0.1 \).

The THz OR in graphene [4] has revealed additional possible mechanisms of ratchet effect: thermoratchet, or Seebeck ratchet arising due to the spatially periodic heating of the electron gas. The latter is independent on the light polarization and therefore has a minor influence on our results (see Figure 2 a)). In addition, the thermal gradient is negligibly small in our sample as its size is similar to the laser spot size.

### 4. Conclusions

We have demonstrated infrared optical rectification arising from electron ratchet transport in a 1D meta-grating composed of two same-period gratings shifted with respect to each other. The OR signal has a maximum at zero incidence angle that is only possible in the structures with broken inversion symmetry. Our design makes use of a second and third order diffraction of the incident laser beam for a 4-fold improved efficiency, as compared with the earlier realizations. We discuss the effects of different known OR mechanisms including thermal, plasmon-assisted non-symmetric photon drag, and ratchet effect.

### Acknowledgements

This exploration drew inspiration from Prof. Shur’s work [3] on helicity-driven ratchet transport, and is enabled by AFOSR (FA9550-19-1-0355); Spectroscopy was done by efforts in ARO W911NF-14-2-0075 and W911NF-2110181.

### References

Up-conversion luminescence activated by surface plasmon polaritons

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Abstract
In this work we discuss remote activation and detection of up-conversion photoluminescence, coming from submicron Er³⁺/Yb³⁺ co-doped nanocrystals (NCs) droplet, deposited locally at one end of long single silver nanowire (Fig. 1). We show that different polarization of the laser beam as well as diameter of the nanowire change optical response of the nanocrystals in this polariton-mediated, remote up-conversion process.

Fig. 1: Experiment geometry [1].

1. Experimental Setup
In the experiment we used scanning confocal fluorescence microscope, equipped with piezo-electrically controlled sample holder and high numerical aperture (1.49) oil-immersion objective (Fig. 2). The microscope was equipped with CW/pulsed fiber-coupled laser diode, operating at 980 nm. The emission signal was filtered by band pass filters (550/40 nm, 650/40 nm), matched to the Er³⁺ emission lines. Luminescence was detected by single photon counting unit and fast PC counter card. For time-resolved experiments we use multiscaler card and programmable signal generator synchronizing the setup [1].

2. Results and discussion
In general, we observed bright NCs emission coming from free end of the nanowire, previously excited by the laser (Fig. 1). This observation indicates that laser beam tightly focused on the free end of the NW launches surface plasmon polaritons (SPPs), which can efficiently propagate through the nanowire and interact with nanocrystals deposited on its opposite end. Interestingly, up-conversion luminescence is activated exclusively by sequential, two-step absorption of plasmon polaritons (instead of photons). Eventually, the up-conversion luminescence is transported by SPPs back to the free end of the nanowire, coupled with the objective [1].

We will show that character of the observed photoluminescence, especially its spectral and time response, strongly depends on the nanowire diameter, laser polarization and configuration of the excitation mode [2] (Fig. 3).

Fig. 2: Scanning confocal fluorescence microscope.

Fig. 3: SEM image of thin and thick silver nanowires and their respective optical response to the laser excitation, polarized perpendicular to the nanowire.

References
Silver nanowires – remotely excited (bio)sensors

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Abstract

We obtained silver nanowires (AgNWs) with varying diameters and lengths by changing a reducing agent during hydrothermal synthesis. We found that proper choice of the reducing agent leads to nanowires with desired dimensions and thus plasmonic properties. For hybrid nanostructures consisting of AgNWs and photoactive proteins we observe that with increase of AgNWs diameter a surface plasmon propagation length increases, yet fluorescence enhancement decreases. Furthermore, we show that as-synthesized AgNWs can be utilized for remote excitation of molecules localized hundred of microns from the excitation spot.

1. Introduction

Metallic nanowires are quite unique nanostructures, as they can support localized as well as propagating surface plasmons. These two effects result in energy propagation along the nanostructure and enhancement of fluorescence intensity in vicinity of nanowires [1,2]. Waveguiding properties of AgNWs give possibility of exciting molecules without directly illumination them. Indirect excitation of molecules can be utilized in construction of (bio)sensors [3] and novel nanophotonic devices [4]. To achieve efficient energy transfer to molecule coupled to silver nanowire two factors must be optimized: (1) energy loss associated with surface plasmon polaritons (SPP) propagating along the boundary of nanowires and dielectric; (2) coupling efficiency between waveguide and molecule. Dimensions of AgNWs influence both these factors and thus lithographic methods arise as suitable way to obtain AgNWs. Nevertheless, such nanowires are polycrystalline, with rough surfaces scattering propagating SPP. The chemical methods of AgNWs synthesis provide an advantage by yielding single-crystalline structures with smooth surfaces, but at the cost of control of AgNWs dimensions [5]. In this work we present how choice of reducing agent during hydrothermal synthesis influences dimensions of silver nanowires and thus their optical properties [6]. We also present that as synthesized AgNWs act as waveguide and can be utilized for excitation of molecules located a hundred micrometers away from the excitation spot.

2. Materials and Methods

2.1. AgNWs synthesis

The AgNWs were synthesized using a hydrothermal method. We used poly(vinylpyrrolidone) (PVP), aniline and hydrogen peroxide as reducing agents. All procedures result in nanowires with lengths of hundreds of micrometers and diameters with the range of 40-250 nm. As synthesized AgNWs are covered by stabilizing, 6 nm thick, PVP cap.

2.2. Fluorescence microscopy

Samples were prepared by spin-coating a mixture of AgNWs, polyvinyl alcohol and photoactive protein (PCP) on a glass coverslip. Peridinin-chlorophyll-protein is a protein with excitation spanning almost the entire visible range, and a narrow emission band at 675 nm. For SPP excitation we used two-objective microscope with independent excitation and emission detection. High NA objective provided confocal excitation with excitation spot <1 µm for 635 nm laser. Emission was collected by another objective in wide-field configuration. For determining enhancement factor another standard wide-field microscope was used combined with 480 nm LED illuminator.

3. Results and discussion

We synthesized AgNWs by hydrothermal method. We have chosen three combinations of reducing agents (1) PVP; (2) aniline; (3) aniline and hydrogen peroxide. All combinations produce AgNWs in length of hundreds of microns and different diameter distributions. Namely, the mean diameter for (1) was 75 nm; (2) 152 nm; (3) 131 nm. SPPs in a single AgNW were excited by illuminating one end of a nanowire with a tightly focused laser beam. Typical images for such illumination are present in Fig.1. We observed bright elongated shapes corresponding to the fluorescence of PCP along the nanowire. Furthermore, this fluorescence is limited to location of the nanowire, since PCP is only excited at the excitation spot and remotely through coupling with the AgNWs. Intensity profiles along each nanowire were extracted and fitted with monoexponential decay function.
Figure 1: Fluorescence intensity maps obtained by two-objective microscope AgNWs (A), AgNWs aniline (B), AgNWs aniline + H$_2$O$_2$ (C), fluorescence intensity profiles along the nanowires (D, E, F,) and distribution of length of propagation for each of the syntheses (G, H, I).

To estimate the fluorescence enhancement, we used wide-field fluorescence microscopy. This time we observed fluorescence originating from the whole sample, but with increased intensity at areas where AgNWs are present. To calculate enhancement, signal gathered from spots where AgNWs couple with PCP was divided by value gathered off the nanowire (non-coupled PCP). Results are presented in Table 1.

Table 1: Comparison of average diameter, length of propagation, and intensity ratio for each synthesis.

<table>
<thead>
<tr>
<th></th>
<th>AgNWs</th>
<th>AgNWs aniline</th>
<th>AgNWs aniline + H$_2$O$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter [nm]</td>
<td>75.8 ± 26.9</td>
<td>152.5 ± 56.1</td>
<td>131.4 ± 42.7</td>
</tr>
<tr>
<td>Length of Propagation</td>
<td>4.1 ± 1.4</td>
<td>6.2 ± 1.8</td>
<td>5.1 ± 1.2</td>
</tr>
<tr>
<td>Intensity ratio</td>
<td>18.9 ± 6.2</td>
<td>5.5 ± 2.0</td>
<td>6.1 ± 1.4</td>
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Finally, we placed a droplet of our photoactive protein at one end of a 100 µm long silver nanowire. When the laser beam was focused on another end of nanowire, we observed fluorescence emission of PCP molecules coupled with the nanowire.

4. Conclusions

Through choice of reducing agent, we can control dimensions of silver nanowires and thus their optical properties. By imaging the fluorescence of PCP coupled with silver nanowires, we found that increasing diameter of AgNWs resulted in longer propagation distance of SPPs, but at the same time lower enhancement of fluorescence intensity. As synthesized nanowires were successfully applied as waveguides to excite molecules at 100 µm distance from excitation spot.

Acknowledgements

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References


Figure 2: Scattering and fluorescence maps of PCP protein deposited on one end of an AgNW and excited from another end.
Optical Probing of Plasmonic Hot Electron Occupancies

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Abstract
We discuss the in-depth distribution and time evolution of hot electrons generated upon the excitation of surface plasmon polaritons. We applied ellipsometry to measure the dielectric function of plasmonic systems and to determine their electron distribution. Applying continuous wave illumination, the spatial location of hot electrons can be deduced. Pump-probe approach with <100fs resolution enabled us to measure electron distributions belonging to stages of plasmon decay when energetic electrons are generated, scattered among each other and interact with the lattice.

1. Introduction
The strong localization of plasmon-assisted photon absorption facilitates the emergence of so-called hot electrons with energy levels that deviate significantly from Fermi-Dirac distribution. In recent years, much attention is focused on these hot carriers, due to their fundamental role in emerging applications.

Here, we demonstrate experimentally the in-depth distribution and the temporal evolution of the surface plasmon polariton mediated hot electron population. For the ultrasensitive probing of hot electron occupancies, we employ spectroscopic ellipsometry, enabling the detection of the energy distribution of the generated hot electrons [1]. As a further benefit, with cw excitation, when the generated SPPs are always present in the system, we can gain information about the location of the generated hot electrons, while pump-probe approach enabled us to determine their lifetime.

2. Methods
2.1. Experiments
For the excitation of SPPs, we applied the Kretschmann-geometry involving a glass right angle prism coated with 50 nm gold by thermal evaporation. SPPs were excited from the backside of the film using either an 808 nm cw diode laser or the 35 fs pump pulses at 800 nm of an amplified Ti:sapphire laser (Coherent Astrella) under resonance angle.

Simultaneously, spectral fingerprints of SPP-related changes were monitored by spectroscopic ellipsometry, illuminating the sample from the top side with a broadband cw light source or white light continuum probe pulses generated from a part of the fundamental beam under 55° and 65° angles of incidence.

2.2. Electron occupancies
From the measured data, the dielectric function of the plasmonic system can be determined. For the interpretation of the measured changes in the dielectric function we exploited its proportionality with the joint density of electron states and electron occupancies [2]:

$$\varepsilon_2(\omega) = \varepsilon_2 \text{ intra}(\omega) + \frac{A}{(\hbar \omega)^2} \int_{\varepsilon_{\text{min}}}^{\varepsilon_{\text{max}}} D(\hbar \omega, E)(1 - f(E))dE$$

where $\varepsilon_2 \text{ intra}$ is the contribution of the intraband electronic transitions, $D(\hbar \omega, E)$ denotes the energy distribution of the joint density of states (EDJDOS), $f(E)$ describes the electron energy distribution. To determine $\varepsilon_2 \text{ intra}$ a Drude function was applied, while to calculate the EDJDOS parabolic band structures were assumed at the L and X points in the Brillouin zone according to [2].

3. Results
Starting with the cw results, it is important to note that in this case, we can gain information about hot electrons due to their continuous generation. Due to the plasmon-assisted electromagnetic field confinement, hot electrons are expected to affect the dielectric function only in the portion of the gold film. Therefore, during our ellipsometric modeling, we divided the gold film into two layers, i) a lower layer with increased temperature exhibiting thermal electron distribution (thermalized layer), and ii) an upper layer accounting for the appearance of SPPs and the associated hot electron generation (non-thermalized layer). As the main result of the ellipsometric analysis, the spatial extent of the non-thermalized layer (1.5-4 nm) and the dielectric function of the non-thermalized and thermalized layers became also available. To interpret the changes of dielectric function we modeled them by assuming different behavior of the electron distribution for the two sublayers.
For the thermalized layer, we applied the Fermi-Dirac electron distribution function, while for the non-thermalized surface layer we assumed electrons having a broader energy distribution described by increased electron temperatures. For the largest applied powers, the distinct peak around 2.3 eV is slightly broadened indicating a more distorted electron distribution [3], which bears also the traces of an additional hot electron population up to ~0.4 eV associated to electron-electron scattering assisted SPP absorption (Fig. 1 b)). These observations provide a clear indication of the existence of a hot-electron population with moderately increased energies close to the film surface where plasmon excitation takes place.

For the pump-probe results, it is not expected that the direct effect of plasmons can be captured due to its very short lifetimes (~10fs) and the time-resolution of the instrument, so the application of the top sublayer was omitted. In this case, we deduced the pseudo dielectric function of the gold layer by direct inversion. Then these dielectric functions were modeled by assuming different electron distributions describing the different mechanisms following the SPP excitation. During the first 100fs the photon absorption perturbs the Fermi-Dirac distribution at energies matching with the excitation energy. Later, a high temperature electron distribution develops. When the energetic electrons interact with the lattice, slight changes are expected near the Fermi energy level accounting for the phonon excitation, and finally the system reaches a thermalized state. By introducing these changes into the electron distribution function, we can compute the corresponding dielectric function which matches nicely with the measured ones (Fig. 2 a) and b)).

Figure 1: a) Measured and simulated differences between the dielectric function of the non-thermalized top layer (NT) and the thermalized part (T) of the gold film and b) the corresponding electron occupancies.

For the thermalized layer, we applied the Fermi-Dirac electron distribution function, while for the non-thermalized surface layer we assumed electrons having a broader energy distribution described by increased electron temperatures. For the largest applied powers, the distinct peak around 2.3 eV is slightly broadened indicating a more distorted electron distribution [3], which bears also the traces of an additional hot electron population up to ~0.4 eV associated to electron-electron scattering assisted SPP absorption (Fig. 1 b)). These observations provide a clear indication of the existence of a hot-electron population with moderately increased energies close to the film surface where plasmon excitation takes place.

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Figure 2: a) Measured and b) simulated changes in the dielectric function of the plasmonic gold layer.

4. Conclusions

In summary, we could detect the development of a hot electron population in a nanometric surface layer induced by the continuous excitation and absorption of SPPs. The signatures of these transient electronic states were revealed with the help of spectroscopic ellipsometry. With pump-probe ellipsometric approach, we could identify the different stages of the SPP decay and the corresponding electron distributions.

Acknowledgements

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References

A refractive index sensor based on a Au inverted honeycomb lattice

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Abstract

We present an efficient refractive index sensor consisting in a Au inverted honeycomb lattice[1]. Numerical simulation showed high sensitivity values up to 99 nm/RIU for test layers of 50 nm. In addition, the figure of merit of the sensor detecting slight changes of the refractive index of a water medium at a fixed wavelength was 199 RIU−1. As an experimental proof of concept, the heterostructure was manufactured by electron beam lithography and the measured optical response agreed with the simulations.

1. Introduction

The design and manipulation of plasmonic nanostructures have rapidly grown interest over the last years, becoming one of the most active fields in nanophotonics. Several plasmonics-based approaches have been applied to improve the detection limit and sensitivity of sensing devices, benefiting from the application of plasmonic structures to confine and manipulate light at a microscopic level. One of the most promising niches for plasmonic nanostructures is their integration in refractive index sensors. This kind of plasmonic sensors benefit from the fact that the wavelengths at which the excitations arise depend strongly on the properties of the medium in which the corresponding near-field distributions can be found. However, the nature of localized surface resonances (LSR) hampers their efficiency as sensing devices since the corresponding evanescent electric near-fields decrease rapidly with the distance from the metal-dielectric interface. To address this issue, inverted structures, in which dielectric holes are carved through a continuous metallic layer, have proven to be a valid approach. In addition, they are known to improve the efficiency of light-matter interaction in several situations [3-6].

2. Discussion

The main goal of the structure presented in this work is to excite plasmonic modes with a near-field distribution that extends far away from the metal-media interface. Our approach is two-fold. On the one hand, the plasmonic structure is, as opposed to a honeycomb array of bars, a continuous layer of Au where bar-shaped trenches are carved through its full thickness (Figure 1). In this way, the near-field distributions shown by such an inverted structure

Figure 1: (a) Top view showing the honeycomb lattice, the hexagonal Bravais lattice (dotted lines), a rectangular unit cell (dashed grey lines), and some relevant parameters of the design. The cell for the simulations is the rectangular unit cell. (b) Schematic cross-sectional view of the structure.
extend further away compared with those arising around direct structures. On the other hand, our system is based on the excitation of surface lattice resonances (SLRs), generating sharper peaks associated with higher-energy modes involving the collective excitation of all the elements in the plasmonic array \([7,8]\). In our case, a SLR is excited at about 765 nm exhibiting hotspots that extend out-of-plane up to 400 nm away from the top Au-air interface. Moreover, the three-fold symmetry of the honeycomb lattice may hamper the excitation of LSR in favor of SLR, making collective modes much more intense \([7,8]\).

Two working modes are pursued in this study. The first one is based on the detection of the refractive index of very thin layers deposited on top of the structure (see Figure 2), reaching a sensitivity of 99 nm/RIU (RIU stands for refractive index units) for a thickness of 50 nm. In the second one, the system is also sensitive to the change in the global refractive index surrounding the structure. In this case, the figure of merit (FOM) defined as:

\[
FOM = \frac{dI/dn}{I_m}
\]

has a value of 199 RIU\(^{-1}\) at a wavelength of \(-974 \text{ nm} [1]\), a remarkable improvement over the results reported in the literature. As an experimental proof of concept, the heterostructure was manufactured by a simple method based on electron beam lithography. The FTIR spectra showed intense and relatively narrow peaks in good agreement with the simulated curves [1].

3. Conclusions

The results shown in this work evidence the high performance of the presented heterostructure based on a Au inverted honeycomb lattice for sensing purposes. Owing to the chosen lattice pitch and because local excitations are hindered by the three-fold symmetry of the honeycomb array, this heterostructure exhibits very intense and narrow reflection peaks corresponding to its collective excitations at wavelengths in the near infrared that are well suited for sensing applications. First attempts to manufacture the heterostructure was done by electron beam lithography and the experimental optical response reproduces the simulations. On the whole, this work paves the way for the application of heterostructures based on inverted plasmonic lattices with three-fold symmetry to improve the performance of a wide range of plasmonic sensors and surface enhanced spectroscopies.

Acknowledgements

We thank Pau Molet and Dr A. Mihi, Institut de Ciència de Materials de Barcelona, for the FTIR measurements.

References


Epitaxial Growth of Single Crystal Noble Metals for Plasmonic and Nanophotonic Applications
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Abstract
Plasmonic structures made from monocrystalline metals display lower absorption losses and a much higher stability than polycrystalline devices which are subject to many losses due to the presence of grain boundaries and defects. With the help of a novel epitaxial electroless deposition chemistry, ultrasmooth gold films are grown on monocrystalline silver surfaces. Our approach enables the growth of gold with improved pattern transfer yield, reduced optical and resistive losses, and tailored local fields to yield greater optical response as compared to those of polycrystalline films.

1. Introduction
Surface plasmons refer to the collective oscillation of free electrons at metal/dielectric interfaces. Their applications include novel waveguide structures in which light can be confined to nanoscopic regions, extraordinary transmission through nanohole apertures, spectroscopy and sensing, negative refractive index materials, as well as solar energy conversion devices [1,2]. However, the efficiency of coupling of photons with the free surface electrons and the propagation distance of surface plasmon polaritons (SPPs) depends greatly on the quality of the metal film [1]. Thus, the growth and patterning of high quality plasmonic materials is needed. Defects on the surface of the metal film will result in scattering of the SPPs back into the far field in the form of photons. The loss of intensity of the SPP can be diminished by achieving atomically flat films [1,3]. Here we show how single-crystal gold and silver, two well-known plasmonic metals, with ultrasmooth surface quality can be deposited at wafer scale.

2. Results and Discussion
Material quality and crystallinity play an important role in the activity of plasmonic nanostructures and metasurfaces. Plasmonic devices made from single-crystal metals are expected to display much higher efficiency and stability than polycrystalline devices which are subject to many losses due to the presence of grain boundaries and defects. It has been previously demonstrated by our group that through novel epitaxial electroless deposition (EED) chemistry, ultrasmooth gold (Au) films can be grown on monocrystalline silver (Ag) surfaces. In this approach, the electrochemical incompatibility of Au and Ag can be overcome in concentrated sodium hydroxide (NaOH) (1 M) where OH⁻ causes a decrease in the reduction potential of Au cations by forming Au(OH)₄⁻ complexes (E=0.57 V), an increase in the oxidation potential of the Ag electrode (E=1.40 V) and acts as a reducing agent. As a result, ultrasmooth monocrystalline Au films are grown with the same crystalline orientation as the underlying Ag film [4].

Figure 1 demonstrates some of the advantages of utilizing this chemistry as compared to the conventional PVD-based techniques. Here, we used focused ion beam (FIB) to fabricate nanostructures on epitaxially grown single-crystal Au and compared the impact of the film quality on the pattern transfer fidelity by fabricating identical structures on a thermally evaporated polycrystalline Au. It can be seen that the uniformity of the crystalline structure of the solution deposited gold leads to a far superior pattern transfer during the ion milling as compared to the vapor deposited polycrystalline film (Figure 1 a-c). The four-point measurement of the Au films showed that the single-crystal Au has 20 times smaller sheet resistance than the polycrystal film. It was also shown that the optical absorption losses have been significantly reduced in single-crystal Au films as compared to the thermally evaporated polycrystalline gold. This chemistry is also compatible with the additive manufacturing processes in which nanolithographic techniques is employed. To demonstrate this, we used electron-beam lithography to create series patterns on PMMA, which is a positive tone e-beam resist. We used the patterned regions to grow single-crystal gold nanostructures by inserting the substrate inside the deposition bath. Figure 3 shows the optical response of a single-crystal Au metasurface as compared with a metasurface array made from polycrystalline Au.

Furthermore, we are exploring opportunities in quantum plasmonics in which we would incorporate an on-demand single/entangled photon emitters based on nanowire quantum dots [5] with these ultrasmooth single-crystal plasmonic films to realize low-loss plasmonic waveguides as components of a hybrid quantum photonic device.
Figure 1. Focused Ion-Beam (FIB) milling of gold structures illustrating the quality of pattern transfer for physical vapor deposited Au, a)-c) left, and epitaxial electrochemically deposited Au in a)-c) right.

Figure 2. Large area additive patterning of single-crystal metal: a) and b) are a SEM of the single-crystal Au nanostructures grown after 5 minutes of deposition, c) is the two-photon excitation image of the Au nanostructures, d) is the SEM of an solution deposited single-crystal Ag and e) is SEM of Ag pillar after deposition of 10 nm Au film, f) and g) are SEM of Au nanowire grown on top of Ag(100).

Figure 3. The comparison of quality of the metasurfaces made of polycrystalline Au,a), and the single-crystal Au,b). The optical responses of the surfaces at 20° incident angle for S- and P-polarized light are shown in e) and f).

3. Conclusions

Epitaxial electroless deposition is a new and cost-effective method to enable the deposition of high-quality single crystal metals from solution. This process is compatible with current nanoscale patterning approaches including focused ion beam milling and electron beam lithography. The method represents an alternative approach to current physical vapor deposition techniques and enables the fabrication of nanophotonic components used in plasmonic metasurfaces and quantum plasmonic devices.

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References


Spherically-shaped WGM resonators for lasers and biodetection

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Abstract
This work presents the results of doping glasses with both silver nanoparticles and quantum dots, fabrication of WGM resonators based on these active glasses and their properties. The authors are mainly interested in applications of such resonators as biosensors, therefore the biofunctionalization tests of glass surfaces was also done.

1. Introduction
Whispering gallery mode (WGM) optical resonators can be used for many applications, such as optical switches, narrow band lasers or thermo- and biosensors [1,2]. Particularly interesting is the application of that resonators in biosensing, due to the significantly enhanced light-matter interactions.

The aim of our work is to prepare the WGM resonators, which can be used to detect exosomes [3]. Exosomes are small vesicles (about 100 nm in diameter) which are excreted by every cell in our body to body fluids (for ex. blood and urine). We want to perform fast, early and non-invasive cancer diagnostics by detecting exosomes from cancerous cells.

2. Discussion
We develop WGM microresonators from fused silica as well as from low-melting materials (like tellurite and phosphate glasses). For our current knowledge, we developed for the first time resonators based on phosphate and tellurite glasses doped with both quantum dots and silver plasmonic nanoparticles. We have achieved this through using the NanoParticle Direct Doping method [4], which is based on one of the crystal growth techniques - the micro-pulling down method.

The microspheres doped with both silver nanoparticles (Ag NPs) and quantum dots (QD) exhibits an unique properties of enhancement excitonic luminescence from QD, by energy transfer from excited plasmonic nanoparticles. Our expectations is to obtain the higher Qfactors of lasing using this phenomenon. The WGM biosensors are based on the resonance shift, so thanks to the increasing Qfactor, we expect higher sensitivity.

The next stage of our work was to cover the resonators with a biologically active material, that will allow us to specifically bind to tumor exosomes. The silanization procedure was used to functionalize the surface, allowing the glass to be coated with antibodies that capture target exosomes. We performed functionalization of WGM resonators with the use of GOPS (3-Glycidoxypropyltrimethoxysilane) silanes based on works by Moller et al. [5]. To verify surface coverage by silanes, silanized samples were placed in a solution of fluorescent oligonucleotide.

Figure 1: The absorbance and photoluminescence of phosphate glass microsphere doped with silver nanoparticles and quantum dots. The narrowband signal at about 510 nm is the effect of enhancement of QD excitonic luminescence by energy transfer from excited plasmonic nanoparticles.
3. Conclusions

WGM resonators doped with both quantum dots, and plasmonic nanoparticles were obtained. Thanks to the enhancement of QD luminescence by excited Ag NPs we expect increase of sensitivity of biosensor. The surface of microspheres can be easily functionalized with antibodies. Our resonators can therefore become an interesting device for sensing applications, where it is very important to detect small amounts of biomaterials.

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The idea and technical realization of the structure for the observation of inverse Faraday effect.

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Abstract

In this work, the idea of the observation of Inverse Faraday Effect (IFE) is presented. The mechanism of the effect is described and the main conclusions from theoretical calculations of IFE in two dimensional electron gas (2DEG) are presented. Finally, the practical realization of the structure for IFE observation is presented. The structure is based on the GaN/AlGaN HEMT structure with back-gate layer. The processing as well as the basic characterization of the structure will be presented.

1. Introduction

The inverse Faraday effect (IFE) was firstly reported by Pitaevskii in 1960 [1]. The mechanism of this effect is as follows. The external electric field $\vec{E}(\omega)$ oscillating with frequency $\omega$ causes circular loop of DC current in a piece of semiconductor. This DC current loop results in appearance of static magnetic field:

$$\vec{M} \propto \vec{E}(\omega) \times \vec{E}^*(\omega)$$  \hspace{1cm} (1)

The first observation of IFE was realised by van der Ziel et al. [2]. In [2] the IFE was seen in the CaFe$_2$:Eu$^{2+}$ crystal. The effect itself is often studied in magnetic materials [3], however, in recent years another approach appeared. It is based on the prediction, that the circularly polarised light can excite the DC current in e.g. the nanoring [4]. This DC current is a source of the static magnetic moment as predicted by eq. 1. In the work [5], the structure presented on Fig. 1

![Figure 1](image1.png)

Figure 1: The structure proposed in ref. [5]. The organized network of nanospheres is placed above 2DEG layer (orange). The 2DEG concentration is controlled by back-gate (violet).

![Figure 2](image2.png)

Figure 2: Plasmonic resonances in optically-induced circulating dc current for different values of the quality factor (here $\gamma = 1/\tau$ where $\tau$ is the momentum relaxation time) [5].

The organized network of nanospheres is placed above the layer with 2DEG. The concentration of 2DEG is controlled by the back-gate, which is represented by violet color on Fig. 1. The electromagnetic wave of circular polarization interacts with the lattice of nanospheres (in fact, the organized periodic network can be considered as 2-dimensional crystal) inducing circular DC current loops. This leads to creation of circular plasmonic modes in 2DEG (see Fig. 2). Due to periodic structure of nanosphere network, only the modes with wavevectors forming reciprocal lat-
tice of the crystal of nanospheres are allowed. In fact, the
gated plasmon mode in 2DEG depends on the period of the
nanosphere network as can be seen from Eq. 2
\[ \omega_p = g \cdot q = \frac{2\pi}{d}, \]
where \( d \) is the lattice constant of \( 2 \cdot \) -dimensional crystal
formed by the nanospheres according to Fig. 1. The fre-
quency of the 2DEG is in range of terahertz, thus leading to
potential application of this effect in THz radiation physics
as well as new devices operating in THz range.

2. The fabrication of the structure.
The epitaxial structure of the sample is presented on Fig. 3.
According to assumptions made in [5], the structure has to
be HEMT - like with conducting layer on the very bottom.
This conducting layer has to serve as a backgate. The sam-
ple was grown on conducting Ammono GaN substrate with
nominal concentration of the order of \( 10^{19} \) cm\(^{-3} \).The epitax-
ial structure was the same at the one described in [6]. On
top of the structure, the periodic lattice of metal disks was
placed with use of electron beam lithography. The disks
were 900 nm wide and the period of the lattice is equal to 2
\( \mu m \). On the same sample, various structures were made by
photolithography, in order to investigate the electrical prop-
erties of the sample. The magnetoresistance measurements
in low temperature (4 K) shows clear Schubnikov - de Haas
oscillations (see Fig. 4).

Figure 3: The epitaxial structure of the sample. The thick-
nesses and aluminum contents are taken from X - ray
diffraction measurements.

The period Schubnikov - de Haas oscillations that can
be seen on Fig 4 was used to calculate concentration of
2DEG in the channel. The obtained concentration was
\( 5 \cdot 10^{12} \) cm\(^{-2} \) which seems to be good result from the point
of view of the observation of plasmonic states.

3. Conclusions
The basic idea of inverse Faraday effect enhanced by
twisted plasmons was presented. The structure for observa-
tion of mentioned effect was shown, as well as its prectical
realization and basic electrical characterization. The concen-
tration of two dimensional electron gas in the channel
that will serve for observation of twisted plasmons was cal-
culated to be around \( 5\cdot10^{12} \) cm\(^{-2} \), what makes the structure
promising basis for further experiments concerning obser-
vation and tuning of twisted plasmon modes.

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Controlling surface plasmons using all-metallic structures

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Abstract

In this work, we propose a method to manipulate and control the propagation of surface plasmons using all-metallic plasmonic structures. In this technique, a metallic structure is inserted within a semi-infinite block made of a different metal. The effective medium approach at each air-metal interface is exploited to control the propagation direction of surface plasmons. As an example, a plano-convex lens is designed and evaluated demonstrating the ability to focus the incident surface plasmons to the desired focal distance.

1. Introduction

The field of nanophononics has emerged as the study of light at nanometer scales [1]. In this realm, plasmonics has become a prominent research area to understand the interaction between light and metallic particles (via Localized Surface Plasmons resonances, LSP [2], [3]) and films (via Surface Plasmons, SPs). SPs are surface waves which propagate along the interface between a metal and a dielectric at optical frequencies. They result from the coupling of electromagnetic radiation with the conduction electrons in metals when the former are modelled as dispersive media [4].

Controlling SPs has gained much interest in both scientific and industrial communities because they provide exciting opportunities for new application in areas such as sensors, focusing devices [5], [6] and nanoantennas [7], among others. Different techniques have been proposed and demonstrated to arbitrarily tailor the propagation of SPs, for instance plasmonic metasurfaces [8], SP graded-index steerable [9], cuboids [10] and micro-disks [11], to name a few. In these examples, a dielectric block placed on the surface of a semi-infinite metal was used to create an effective refractive index ($n_{\text{eff}}$) for the excited SPs propagating in such effective medium. In so doing, focusing and steering of SPs can be achieved by properly engineering the height of the dielectric in the direction perpendicular to the propagation direction [12].

Motivated by the need of an arbitrary manipulation of SPs and the opportunities they offer in a wide range of applications, in this work we propose a mechanism to manipulate the propagation direction of SPs by using all-metallic structures for ultra-compact devices. In our approach, a metallic block made of silver (Ag) is inserted in a semi-infinite metallic substrate of rhodium (Rh). The design of the SP lens is based on the different values of $n_{\text{eff}}$ produced in the Air-Ag and Air-Rh regions. A plano-convex lens with a focal length of $2\lambda_0$ at the wavelength of $\lambda_0 = 360$ nm is designed as an example demonstrating how surface plasmons can be focused to a single spot using all metallic plasmonic structures.

2. Design and Results

A schematic representation for an arbitrary all-metallic structure is shown in Fig. 1. The shape this insert takes will determine the effect it has on the surface plasmons. In this study, a semi-infinite block of silver (Ag) was inserted into a semi-infinite slab made of rhodium (Rh). As observed, we can define two regions where surface plasmons will travel: i) Air-Ag and ii) Air-Rh (see insets in the same Figure). Hence, to determine the shape of the inserted structure, we can first calculate the effective propagation constant for each region using the well-known expression $\beta_{\text{eff}(a,b)} = k_0 \sqrt{(n_0^2 n_{\text{met}}^2)/(n_0^2 + n_{\text{met}}^2)}$ [13] with $a$ and $b$ as the interfaces Air-Ag and Air-Rh, respectively, $k_0$ is the wavenumber in free space, $n_0$ and $n_{\text{met}}$ are the refractive index of air and the metal (Ag or Rh) respectively. This can then be used to calculate the effective refractive index at Air-Ag and Air-Rh by simply using $n_{\text{eff}(a,b)} = \beta_{\text{eff}(a,b)}/k_0$. Finally, the profile of the lens can be designed using the general equation of a conical section (see ref. [14]). The all-metallic focusing device was designed at $\lambda_0 = 360$ nm, at

![Figure 1. Schematic representation of the proposed all-metallic structure. The panels on the bottom row represent each of the air-metal interfaces.](image)

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Figure 2 (a) Numerical results of the x component of the electric field on the xz plane. (b) The normalised power at the focal length (dashed line) of the lens.

which \( n_{\text{eff}(a)} = 1.028 \) and \( n_{\text{eff}(b)} = 1.317 \), to produce a focal spot at the focal length (FL) of \( 2\lambda_0 \). The structures where numerically evaluated using the transient solver of the commercial software CST Microwave Studio® and the numerical results of the \( E_x \) field distribution just at the interface between air and the metallic structures are shown in Fig. 2(a) where it can be observed how a clear focus is produced. These results are in agreement with the designed values with a numerical FL at 493nm and a Full-Width at Half-Maximum (defined as the distance at which the power distribution, which can be seen in fig. 2(b) has decayed half its maximum along the transversal \( z \) direction at the FL) of FWHM = 540nm. The results presented here can be extended to other configurations such as SP steers and all-metallic plasmonic sensors [15]. Our efforts to develop a wider range of applications using all-metallic structures applying the proposed approach will be presented in more details during the conference.

3. Conclusion

In conclusion, in this work a focusing device for surface plasmons has been proposed using all-metallic structures. The lens was designed by exploiting the effective refractive index produced at the interface between a semi-infinite metal and a dielectric (air in our case). A clear focal spot was demonstrated close to a distance of \( 2\lambda_0 \) from the output surface of the lens, in agreement with the designed values. The proposed approach may open new avenues in the arbitrary control of SPs using ultra-compact all-metallic structures.

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New Artificial-Intelligence Techniques for Electromagnetic Metastructures

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ABSTRACT

A survey of the new artificial-intelligence (AI)-based approaches for analysis, design, optimization, and knowledge discovery in electromagnetic nanostructures will be presented. Recent advances in using both deep-learning (DL) techniques and machine-learning (ML) techniques and their application to practical problems will be covered. These techniques will not only enable more efficient designs of the electromagnetic nanostructures (e.g., metasurfaces), but also provide valuable insight about the physics of light-matter interactions in such structures. Details of the training process for these algorithms as well as the challenges and limitations of these techniques for different classes of nanostructures will be discussed. Knowledge discovery using these techniques includes the study of feasibility of a certain response from a given nanostructure and comparing the roles of different design parameters to facilitate the training process.
Design of Active and Reconfigurable Metasurfaces

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Abstract

A grand challenge for nanophotonics is the realization of comprehensively tunable metasurface nanoantenna arrays enabling dynamic, active control of the key constitutive properties of light – amplitude, phase, wavevector and polarization. Achieving this will open new photonics applications in phased-array optical beam steering, visible light modulation for communications and thermal radiation management. This tutorial will discuss design approaches for active and reconfigurable metasurfaces including selection of active materials, electromagnetic design and time-modulation. We will also survey status and outlook for electronically tunable and reconfigurable plasmonic and all-dielectric metasurfaces, whose elements are arbitrarily reprogrammable, enabling a wide array of functions, including steering, focusing, and frequency multiplexing of scattered radiation.
Metasurface Flat Optics: from components to mass manufacturing to systems

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Abstract

Flat optics based on metasurfaces has emerged in recent years as a promising alternative to refractive and Fresnel optics in many applications, due to the smaller footprint, mass-manufacturing using the same technology of semiconductor chips, easier control of aberrations and multifunctionality. I will cover recent advances in components and show how they have led to breakthroughs in cameras and other systems such as ultra compact spectrometers.
Non-classical light source with single photon and squeezing properties in a nanoscale photonic-crystal-plasmonic system

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Abstract

Single photon and squeezing properties are important in on-chip quantum applications. Single photon sources were investigated in various microstructures. However, on-chip squeezing light sources remain exploring. Here, a photonic-crystal-plasmonic nanostructure is proposed with strong mode-emitter coupling from a band-edge mode. Our calculation shows non-classical light is achieved with degree of squeezing 0.46 dB and $g^{(2)}(0) < 0.1$ under strong coupling. Besides, 70\% emission are channeled in the 2D line defect. The system provides possibilities to on-chip versatile non-classical light sources.

1. Introduction

The features of non-classical light such as single photon property, squeezing property and photon entanglement play central roles in many quantum applications such as quantum computing and sensing. Therefore, non-classical light sources are widely investigated for practical devices. An effective method to generate non-classical light is strong coupling between an emitter and a microcavity, which could generate single photon properties from photon blockade and squeezing properties with reduced quantum noise.

Single photon sources have been studied in various micro- or nanostructures. For example, photonic crystals, micropillar cavities and whisper-gallery-mode resonators are utilized to achieve strong coupling under their ultrahigh Q factors. However, the generation of squeezing light by strong coupling remains further exploration for on-chip applications.

We propose a photonic-crystal-plasmonic system possessing a band-edge mode with a narrow linewidth of 3 meV. Our calculation shows that, under the strong coupling, single photon and squeezing properties can be simultaneously achieved, and they can be modulated with Kerr effect from silicon materials. The 2D line defect in the system also brings convenience to photon out-coupling. The proposal provides a candidate for on-chip multifunctional non-classical light sources.

2. Setup of photonic-crystal-plasmonic system

As shown in Figure 1, the proposed system is composed of a silicon photonic crystal (PC) waveguide, a silver nanoparticle and a two-level emitter. The PC waveguide is made by removing an entire row of air holes, the nanoparticle is buried in the lattice region and an emitter is placed near the nanoparticle. The nanostructure possesses a band-edge mode, which occurs at the band edge of PC. Its very narrow linewidth ($\kappa \sim 3$ meV) in the absorption spectrum [Figure 1] means the decrease of decay of the optical mode. PC structures also suppresses the radiation to other modes that the emitter decay $\gamma$ is limited to 0.2 meV. Besides, the mode-emitter coupling strength $g$ reaches 4.2 meV, which provides a condition for strong coupling $g > \kappa, \gamma$. Additionally, the frequency of the band-edge mode can be shifted by Kerr effect enabled by silicon materials.
The system is also suitable for squeezing in our system. Particularly, at the band edge, the pump strength to excite the emitter, and $\sigma(\sigma^\dagger)$ are cavity-mode and emitter operators. By calculating the steady-state solutions, the single photon and squeezing properties can be acquired.

$$\mathcal{H}_{\text{eff}} = \left(\Delta_a - \frac{ik}{2}\right) a^\dagger a + \left(\Delta_c - \frac{iy}{2}\right) \sigma^\dagger \sigma + g(a^\dagger \sigma + a \sigma^\dagger) + \mathcal{E}(\sigma + \sigma^\dagger),$$

Due to the Kerr modulation enabled by silicon materials, the frequency of the band-edge mode $\omega_c$ can be shifted. As a result, $\Delta_a, \Delta_c$ can be independently tuned in our system. The results as a function of $\Delta_a, \Delta_c$ are depicted in Figure 2. Around $(\Delta_a, \Delta_c) = (+4, \pm 4.5$) meV, single photon and squeezing properties can reach an optimized level. Particularly, at $\Delta_c = -3.40$ meV and $\Delta_a = -4.35$ meV, $g^{(2)}(0) = 0.098$ and $(\Delta X_3^2)_{\text{min}} = -0.025$ (degree of squeezing 0.46 dB).

![Figure 2](image)

Figure 2: The lowest value of normal-ordered quadrature fluctuation $(\Delta X_3^2)_{\text{min}}$ (upper panel) and the second-order correlation function (lower panel) when $\Delta_a, \Delta_c$ vary.

The system is also suitable for photon out-coupling in on-chip devices. The 2D line defect provides a channel for effective transmission of non-classical light. Our calculation demonstrates that the coupling efficiency $\beta > 70\%$, which indicates that 70% of emission can be transmitted through the line defect. Meanwhile, non-classical remains with $g^{(2)}(0) = 0.04$ and the degree of squeezing 0.33 dB.

4. Conclusion

The proposed photonic-crystal-plasmonic system demonstrates its ability to generate and modulate non-classical light properties. The second-order correlation function $g^{(2)}(0)$ can be lower than 0.1 and the degree of squeezing reaches 0.46 dB. Moreover, the photon can be well channeled to on-chip devices by a line defect with coupling efficiency $\approx 70\%$. It may inspire more relevant work on on-chip versatile non-classical light sources.

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Optomagnetic field in nonmagnetic plasmonic nanostructures

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Abstract
Using simplified hydrodynamic model, we theoretically investigate resonant inverse Faraday effect within individual plasmonic nanostructures. Upon illumination with circularly polarized light, resonant nanostructures are shown to develop an optomagnetic field that is controllable by the helicity of the light. Given their submicron footprint, individual plasmonic nanostructures open new prospects towards ultrafast and polarization-controlled tunable magnetism on the nanoscale, thus potentially impacting large panel of applications including all optical magnetization switching, spin-wave excitation and optomagnetic tweezing of nano-objects.

1. Introduction
Optically-induced magnetism has drawn considerable interest in the past years for its ability to speed up magnetic processes[1]. For example, static magnetic fields have been demonstrated to be generated in nanometric plasmonic (gold) nanoparticles and nano-apertures [2, 3]. Such a phenomenon has been analyzed as the result of the inverse Faraday effect [4, 5, 6]. Inverse Faraday effect in plasmonic structures can be predicted with a hydrodynamic description of the free electron gas of a metal [5, 7]. More generally, the hydrodynamic model provides reference equations for describing optical nonlinearities in plasmonic nanostructures [8, 9, 10, 11].

In the context of the hydrodynamic model, the electron fluid density n(r,t) and the electron velocity field v(r,t) satisfy Euler’s equation

\[ \frac{\partial v}{\partial t} + (v \cdot \nabla)v = -\frac{1}{\tau}v - e/mE_e + \mu_0 e/mv \times H_e - \frac{\beta^2}{n} \nabla n, \] (1)

And the continuity equation reads as:

\[ \nabla \cdot j_e = -\frac{\partial n}{\partial t}, \] (2)

where \( j_e = n_e e \) is the linear current density, \( \gamma_e \) is conductivity, \( E_e \) and \( H_e \) are applied fields, \( m \) is the effective electron mass, \( \tau \) is the electron collision time, \( n_e \) is electron fluid density, \( v \) is electron velocity. The last term in the equation 1 is due to the electron gas pressure, with \( \beta \) proportional to the Fermi velocity \( v_F \). This term describes nonlocal effects. The 3D numerical solvers of such a hydrodynamic model require computational power and are time consuming [12].

In case of smooth and slowly varying \( n \) it is possible to neglect nonlocal effects (\( \beta \rightarrow 0 \)) and take into account only local response [11]. This local response approximation avoids the resolution of a complex nonlocal equation [5, 6], however this approximation limits the model predictions to bulk. Prediction of surface effects become inaccurate and ambiguous due to strong variation of electron fluid density [9, 11, 13, 14]. We have developed a simplified hydrodynamic model which enables to stay within the local approximation and overcome the ambiguity at the interfaces.[15, 16]. Simplifying the hydrodynamic model required to rigorously describe optomagnetism in noble metals [17] helps leaving basic nanoparticle geometries and addressing optomagnetism in more complex 3D nanostructures usually obtained from top-down nanofabrication techniques.

2. Simplified hydrodynamic model
This method consists of defining a thin metal layer beneath interfaces, whose thickness matches Thomas-Fermi length (\( \lambda_{TF} \approx 0.1 \text{ nm} \) for noble metals). This layer is considered to be a surface/interface layer, where the electron gas pressure is considered to be high. Out of this layer, in the metal bulk, the local model applies (\( \beta \rightarrow 0 \)). Within the interface layer, the parallel component of the linear current density \( j_e^p \) preserves whereas the normal component \( j_e^N \) decays to zero. This additional boundary condition on \( j_e^N \), which is required to solve the nonlocal problem, is attributed to a neglected electron “spill-out” at interfaces [11]. The new boundary condition enables to solve the simplified hydrodynamic model in perturbation approach and find the expression for bulk and surface DC currents. It has been demonstrated that the main contributors to the optomagnetic response are surface currents [2, 4, 5, 7, 15, 16, 17, 18]. The azimuthal component of the surface current reads as:

\[ [j_{dN}^\alpha]_{\parallel} = \frac{\tau}{n_0 e} \text{Re} \left[ \left( 1 + \frac{i \gamma_0}{\omega \tau} \right) j_e^N(0^-) j_e^\alpha N(0^-) \right]. \] (3)

Defining \( \xi \) as the spatial coordinate normal to surfaces so that the metal bulk is located at \( \xi < 0 \) and the surface layer corresponds to \( 0 < \xi < \lambda_{TF} \), we have \( j_e^N(\xi) \approx j_e^N(0^-) \) and \( j_e^\alpha N(\xi) = j_e^N(0^-) \sigma(\xi) \), where \( \sigma \) is a decaying function defined by \( \int_0^{\lambda_{TF}} \sigma(\xi) d\xi = -1 \) where \( \sigma' \) is the derivative with respect to \( \xi \) [11].
3. Results

Using our simplified hydrodynamic model we have predicted the optomagnetic response of a 50 nm-diameter and 12 nm high silver cylinder in a medium of refractive index equal to 1.45 (Fig. 1) and 70 nm- inner diameter and 50 nm high coaxial nanoaperture of gap size equal to 10 nm (Fig. 2). Both nanostructures are illuminated with a right-handed circularly polarized gaussian beam propagating along the axis of symmetry (Oz) of the structures.

![Figure 1](image1.png)

**Figure 1:** (a) and (b) Distributions of amplitude of the optically-induced static magnetic field in a longitudinal cross-section (x0z) of the cylindrical plasmonic nanostructure in oil. Illumination is realized with a circularly polarized light of intensity $3 \cdot 10^8$ W cm$^{-2}$ at $\lambda = 649$ nm. The local optomagnetic field orientation is represented with white arrows.

![Figure 2](image2.png)

**Figure 2:** Distributions of amplitude of the optically-induced static magnetic field in a longitudinal cross-section (x0z) (a) linear scale (b) log scale. The nanostructure is an annular nanoaperture in gold laying on glass substrate. Illumination is realized with a circularly polarized light of maximum intensity $0.5 \cdot 10^{13}$ W cm$^{-2}$ at $\lambda = 800$ nm. The local optomagnetic field orientation is represented with white arrows.

4. Conclusions

On the basis of the simplified hydrodynamic model of the free electron gas of a metal, we investigate the generation of an optomagnetic field (generated from the inverse Faraday effect) in plasmonic coaxial structures upon illumination with a circularly polarized light. We also show that the substrate introduces an important asymmetry of the optomagnetic response of the plasmonic nanostructure. The optomagnetism is mainly localized within the substrate, which appears to be advantageous for many applications.

Optomagnetism in plasmonic nanoapertures may impact a broad field of applications and techniques including spintronics, magnonics and data storage via the development of on-chip nanoscale plasmonic-magnetic architectures. Optomagnetism may also provide new degrees of freedom in nano-object tweezing based on the combination of optomagnetic and pure optical forces.

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Fabrication of SERS Substrates via Laser Induced Surface Nanostructuring of Silicon

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Abstract

In this work, we fabricate SERS substrates using laser assisted chemical etching as a surface nano structuring technique for crystalline silicon surface. On top of the surface of the etched silicon, silver is thermally deposited to form hot spots with the roughened surface. Silver thickness on top of the structured silicon is shown to influence significantly to the SERS signal obtained from the substrates due to electromagnetic field enhancement, along with the various parameters that affect surface roughness of silicon, such as, illumination power, duration, and solution concentrations.

1. Introduction

Surface-enhanced Raman spectroscopy (SERS) technique dates to 1977 [1], however, possibilities for substrate fabrication methods and configurations constantly increase since then. Moreover, numerous potential applications in the fields of material science, biology, chemistry, and food industry keep the SERS technique as hot topic [1][2]. There are numerous fabrication methods to enhance the Raman signal of a substance in the literature. This enhancement can be mainly achieved either by chemically changing the polarization due to charge transfers with the molecule or by creating plasmonic hot-spots on the surface of a substrate. The second way, namely, local enhancement of electromagnetic field in nanoscale, requires plasmonic materials like silver and gold nanostructures seem to have the most powerful enhancement on the Raman signal. And since there are numerous ways to produce or synthesize plasmonic nanostructures, it directly means that there are plenty of configuration of which electromagnetic field can be enhanced, in other words, hot spots can be formed [3][4][5][6].

Yet, a significant portion of these methods rely on adsorbing plasmonic nanoparticles on a substrate to enhance the signal within the hot spots created. In this work, we use another approach to form these hot spots; by chemically etching the silicon substrate under laser illumination [7][8] and thermally depositing silver onto the etched substrate.

Silicon surface structuring techniques are sometimes quite functional and more convenient than thin film coating or adsorbing chemicals onto the flat surfaces and these etching methods are used in plenty of applications like sensing, anti-reflection coatings in photovoltaics, SERS substrates etc. Crystalline silicon surface can be structured in many ways; directly by pulsed laser, plasma, and wet etching [8]. In the wet etching category, we use the method of laser-assisted chemical etching, where the etching reaction of hole generation is ignited by laser illumination instead of electrodes or metal. In this way, nano holes are created on the surface of the silicon. When combined with the silver coating on top of the etched surface, the substrate experiences local field enhancement when excited by laser illumination in Raman spectroscopy.

2. Experimental

The initial step towards the fabrication of SERS substrates we produced is laser-assisted chemical etching of silicon. A polished n-type (100) mono crystalline silicon wafer immersed in an HF and peroxide solution is illuminated by CW 532 nm laser. On the surface of illuminated area, nano holes are created as in the Figure 2, as a result of the anodic dissolution of silicon and cathodic reduction of hydrogen peroxide, the oxidant. These etching structures highly depend on the laser power, illumination time, and the concentrations of water, oxidant, and HF in the
Silicon wafer type, doping level and illumination wavelength also affect the whole process, however, in this study, those factors are kept same for simplicity.

In the experimental setup for laser-assisted wet etching process shown in Figure 1, laser beam coming from the CW 532 nm light source is directed via the mirrors and lenses onto the micro-mirrors of Digital Micromirror Device (Texas Instruments DLP6500 DMD) [9] which shapes the incoming beam by opening and closing its pixels through the software. Then, the shaped laser beam, e.g a square pattern, is reflected to the container with the samples immersed in the HF solution. The beam shape control through DMD ensures that a more specific area of the silicon wafer is etched homogeneously, while the rest of the sample remains flat. However, utilization of DMD is not limited with the beam shape, it also provides duration control over the micro-mirrors. Thus, one can adjust different exposure times of the incoming laser beam.

After the etching process, silver is deposited via thermal evaporation technique onto the surface of the etched silicon. The substrates with silver thickness from 30 nm up to 100 nm are fabricated in this study, while the depths of nanoholes on silicon vary from 50 nm up to 200 nm with an average of 100 nm.

As a final step, the Raman active molecule to be examined is spin coated onto the substrate composed of etched silicon and thin film silver. The dye molecule Brilliant Cresyl Blue (BCB) is used as Raman active molecule on the substrates down to the $10^{-11}$ M dilution. Diluted aqueous solution of 0.05 mL BCB is spin coated at 1000 rpm for 1 minute.

The substrates are characterized by Scanning Electron Microscope (SEM) and Atomic Force Microscopy (AFM) techniques, and nanohole densities are analyzed by Reflection/Transmission measurements and via the relevant softwares of both electron and optical microscopy images. The Raman Spectroscopy setup consist of CW 532 nm laser, A Nikon Eclipse LV100 microscope equipped with a 100X/0.90 NA Nikon objective used in excitation of the sample and collection of the signal and f/9.8, 750 mm spectrometer (Andor SR750) with 150 l/mm grating and Andor newtonEM CCD camera. The laser power reaching to the substrates is 9 mW.
3. Results and Discussion

One of the main focuses in this work is to investigate the silver thickness dependence on the SERS signal enhancement [10]. Keeping the laser-assisted wet etching parameters on the silicon and Raman molecule molarity constant, the effect of silver thickness on the SERS enhancement mechanism is observed on the figures below. The maximum SERS signal is obtained for thickness values between 40-60 nm silver coating. Below and above these values, the effect of plasmonic resonance on field enhancement starts to decrease. These thickness values certainly have something to do with the depth of nano-holes. As the average hole depth is in the 100 nm order, after 100 nm of silver coating the etched surface is fully covered and the nanoscale effects of the hot-spots are mostly eradicated. Conversely, below the 40 nm of thickness, silver is deposited non-uniformly throughout the rough surface, which results in weak Raman signal due to weaker plasmonic effect.

In the same silver thickness, most enhanced Raman signals are observed from the substrates with dense etched surface and no significant signal is obtained from silver on flat silicon surface. On the other hand, merged and wider nano holes formed by higher etching tend to decrease the field enhancement due to cancellation of hot spots. This fine line can be achieved by adjusting the appropriate illumination power, etching duration, and HF/oxidant concentration in the solution.

Figure 5 graphs shows the effect of laser power, duration of laser illumination, and the beam spot size on the SERS signals from the substrates produced with such parameters. In the Raman measurements from these substrates, silver thickness is kept at 50 nm and the BCB molarity is \(10^{-3}\) M for all the samples. The beam spot size is adjusted merely by DMD by keeping the laser output power constant. The reason for the Raman signal drop due to smaller spot size is that as the laser intensity goes higher with decreasing beam area, etched holes on the silicon surface become larger and reach the micron scale. Thus, as mentioned above, merging or widening of the holes diminish the electromagnetic field enhancement coming from the hot-spots.

Figure 4: Two samples in the same solution and wafer parameters etched by different spot size (1 mm above, 5 mm below) through DMD. The nanoholes enlarge to the micron scale as the beam size gets smaller.

Figure 3: Silver film thickness dependence of SERS intensities for \(10^{-3}\) M BCB.
Figure 5: Comparison of the SERS intensities for the substrates produced with different etching power, duration, and spot size but with the same silver thickness of 50 nm and 10⁻⁵ M BCB. Each line represents the area under the characteristic BCB peak around 1620 cm⁻¹.

As a result, significant enhancement with EF up to 10⁷ for the substrates fabricated with 50 nm silver thickness, laser-assisted chemically etched around 200 mW illumination power and 15 minutes of etching duration is achieved and the characteristic Raman shift peaks of BCB is observed down to 10⁻¹¹ M of the analyte molecule.

Figure 6: Limit of detection for BCB down to 10⁻¹¹ M and the noisy signal coming from the silver on flat silicon region with silver thickness of 50 nm for all.

4. Conclusions

A significant enhancement of Raman scattering signal is obtained using these fabricated substrates composed of the hot spots created via laser assisted chemical etching of silicon and suitable thickness of the silver coating. Furthermore, silicon roughness is shown to be greatly affected by illumination power, duration, and beam spot size along with the HF and oxidant concentrations in the solution of which silicon wafer is immersed. These roughness parameters thus alter the hot spot size and distribution for the SERS substrate and highly influence the Raman signal intensity.

5. Acknowledgements

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References


Quantum and topological photonics
Spontaneous emission enhancement of handed molecules

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Abstract

A theory of interactions of nanostructured quantum vacuum with atomic systems beyond the electric dipole approximation has recently been developed. Based on that input, in this work we investigate spontaneous emission enhancement of right- and left-handed molecules via the Purcell effect in proximity of plasmonic or dielectric nanocavities. Our conclusion is that the handedness of an atomic system may have major influence on its emission rate in suitably tailored nanophotonic environments.

1. Introduction

Nanostructured cavities made of plasmonic or dielectric materials offer a suitable platform for enhancement of light-matter interactions. A canonical phenomenon in this context is the Purcell enhancement of spontaneous emission of atomic systems positioned at close vicinity of nanoparticles. These nanoparticles act as cavities in the sense that they confine and enhance electromagnetic energy into subwavelength spatial domains, where the atomic systems can be localized. This problem has been extensively studied, and recently it was pointed out that the electric dipole approximation for the light-matter interaction may not be sufficient to accurately describe Purcell enhancement in nanophotonics. Several extensions beyond this approximation have been proposed [1, 2, 3, 4, 5, 6]. While the approaches introduced in Refs. [1, 2, 3] in principle include all multipolar interaction orders, they require access to full wavefunctions of the atomic systems. Contrary, the method proposed in Refs. [5, 6] is based on multipolar transition moments which in some cases may be more practical. Here, we apply the latter approach to the problem of Purcell enhancement of spontaneous emission of chiral, right- or left-handed molecules.

2. Spontaneous emission of handed systems

Quantum state transitions of molecules or atomic systems in general, are characterized with electric and magnetic multipolar moments. In particular, a transition electric dipole moment between an excited state $|e\rangle$ and a ground state $|g\rangle$ is $d_{eg} = \sum q_i <e|r_i|g\rangle$, where $r_i$ and $q_i$ represent respectively the position operator and the charge of the $i$th charge of the system, and similarly for the magnetic dipole and higher-order moments. Depending on the eigenstate geometry, these moments can have various orientations, whose interplay defines the optical response of the atomic system. In particular, molecules which have transitions with parallel (antiparallel) components of the corresponding magnetic and electric dipoles, are right- (left-) handed. This property is manifested in particular through circular dichroism, i.e. differential absorption of right- and left-circularly polarized light.

In this contribution we note that the same property could be reflected in spontaneous emission near nanostructured scatterers. Let us consider a molecule with parallel or antiparallel electric and magnetic dipole moments. Then, its spontaneous emission is a sum of three contributions: of purely electric-dipole origin, purely magnetic-dipole origin, and their interference. The latter term has a different sign for the right- and left-handed transitions. This means a left-handed molecule may have a different transition rate than a right-handed one provided that the interference term is nonzero.

To have a better insight into this phenomenon we evaluate a difference in spontaneous emission rates of right- and left-handed molecules according to the theory developed in Ref. [5]

$$\Delta \Gamma = \frac{4\mu_0\omega_{eg}}{\hbar} d_z m_z \times$$

$$\times \left\{ \partial_z \text{Im}[G_{yz}(r, r_0, \omega_{eg}) + G_{zy}(r, r_0, \omega_{eg})] \right\}_{r = r_0}$$

$$- \partial_r \text{Im}[G_{xx}(r, r_0, \omega_{eg}) + G_{zx}(r, r_0, \omega_{eg})] \right\}_{r = r_0},$$

where $\mu_0$ stands for vacuum permeability, $\omega_{eg}$ is the transition frequency, $\hbar$ is the reduced Planck’s constant, and without loss of generality we have assumed both electric $d$ and magnetic $m$ dipole moments to be oriented along the $z$ axis.
Figure 2: Two leading contributions to the spontaneous emission rate difference between the right- and left-handed molecules, in function of position of the molecule between two silver nanoparticles, as sketched in Fig. 1. All values is nm$^{-2}$. Reprinted from Ref. [5].

of a coordinate frame. The elements of the Green’s tensor of the medium are denoted as $G_{m,n} \in \{x, y, z\}$. Their explicit form depends on the geometry of the nanophotonic environment and determines its optical response. Spatial derivatives $\partial_{x,y}$ of the imaginary part of the tensor are taken over the first argument and are evaluated at the position $r_0$ of the molecule.

We note that only off-diagonal components of the tensor contribute to this quantity. Therefore, in free space or in a homogeneous isotropic medium, as expected, the spontaneous emission rate of a molecule should be independent of its handedness. However, this can change in close proximity of a scatterer, and the influence of handedness may become significant if distance to the scatterer is nanoscopic, as we now demonstrate with an example.

3. Example
We evaluate the quantity in Eq. (1) for an example geometry given by a dimer of silver nanospheres of 20-nm radii separated by a 6-nm gap (Fig. 1). We find the spontaneous emission difference to be maximized for an orientation of the magnetic and electric dipoles horizontal in Fig. 1, i.e. perpendicular to the one that connects the nanospheres and optimizes the traditionally investigated, purely electric-dipole Purcell enhancement. The leading contributions are shown in Fig. 2, while the other two derivatives are suppressed by three orders of magnitude and not presented. Please note that for a typical set of molecular parameters, i.e. an electronic transition at a free-space wavelength of 500 nm, transition dipole moments equal to 1 atomic unit for each electric and magnetic dipole channels (corresponding to $d_z = 8.5 \times 10^{-30}$ Cm and $m_z = 1.9 \times 10^{-23}$ J/T in SI units) and for the Green’s tensor’s derivative of 0.1 nm$^{-2}$, we find $\Delta \Gamma \approx 300$ MHz, which is the scale of modulations in Fig. 2.

4. Conclusions
We have investigated the difference in spontaneous emission rates of right- and left-handed molecules depending on their nanostructured surroundings. For an example geometry we have obtained a significant difference, which would vanish in free space. We have based these results on the theory developed in our previous works. A comprehensive study of the effect for different molecular orientations and other nanostructured geometries will be the subject of our contribution to the META conference.

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References
Strongly Extended Many-Body Enhancement in Diamond Epsilon Near-Zero Metamaterials

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Abstract

We demonstrate analytically and numerically that with a diamond epsilon near-zero (ENZ) metamaterial with design we experience an ultra-high cooperative enhancement over distances greater than 10 microns for both two emitters and many-body ensembles of dipoles.

1. Introduction

As the field of experimental quantum information has exploded in the past decade, physicists have made countless efforts to create scalable implementations of quantum optical phenomena. The fields of quantum optics and nanophotonics have merged to demonstrate photonic crystal cavity quantum electrodynamics (QED), nanoscale spectroscopy, and a variety of other light-matter interactions. However, for most nanophotonic systems these interactions are limited to relatively small numbers of atoms and over small spatial extents relative to optical wavelengths.

Superradiance is a many-body phenomenon in which atoms radiate coherently with one another, and the effect of constructive interference leads to an N-fold increase in the spontaneous emission rate \([1,2]\), where \(N\) is the number of atoms. Classically we can interpret this as an \(N^2\) scaling in the power for this ultra-coherent emission compared to simply an \(N\) scaling for incoherent emission. From a quantum mechanical perspective, superradiance corresponds to a cooperative enhancement of decay rate as well as enhancement in power. The key requirement for this effect is that all of the atoms need to be within one wavelength from one another, \(i.e., k_o R < \lambda\) for a wavevector \(k_o\) and a distance \(R\). If the atoms are not within a wavelength, the phase matching conditions for perfect coherence become increasingly complex in large systems in more than one dimension.

Because of the lack of spatial phase advance in zero-index metamaterials (ZIMs) and specifically ENZ metamaterials, we can obtain near-perfect superradiance throughout space with low radiative loss in ZIMs. We therefore propose to use our metamaterial platform to achieve superradiance of many atoms in a highly extended two-dimensional sample. This will enable us to explore applications of cooperative quantum phenomena with many emitters in a compact platform in future experiments.

2. Analytic Many-Body Superradiance

For the case of many-atom superradiance in ZIM, we will be initially following the derivations presented in [3]. We will be following the Wigner-Weisskopf approximation of spontaneous emission, creating an ansatz wavefunction comprised of a sum of \(N\) Dicke states each with a component representing the possible number of photons in the environment. Inserting the ansatz wavefunction into the Hamiltonian presented in (cite) we create a series of coupled equations with decay rate terms \(\gamma\) and coefficients representing populations for the Dicke states. Figure 1a demonstrates the decay rate enhancement for a set of different uniform indices of refraction.

Figure 1. a.) Plot of decay rate over inter-dipole distance for 1000 atoms at different refractive indices. b.) Effective permittivity and permeability of 2D design. c.) Log-log plot comparing the total output power normalized to a single...
emitter for different array sizes. d.) Plot showing power enhancement over wavelength for different pillar array

3. Epsilon Near-Zero Metamaterial Design

![Image](image_url)

Figure 2: a. Two-atom decay rate enhancement comparing ENZ metamaterial, a homogenous material with the same refractive index, and free space. b.) decay rate of a 51x51 2D array of dipoles in bulk diamond at various spacings. c.) Imaginary field enhancement for a 51x51 array of dipoles in the ENZ metamaterial and d.) a homogeneous material with the same refractive index and dipole configuration.

We achieve an epsilon near-zero metamaterial in a 2-dimensional square array using full-wave numerical simulations (Lumerical FDTD). We design the diamond-based epsilon near-zero metamaterial in the form of a square array diamond pillars. We optimize the pitch and radius of this structure to achieve an effective index of zero with low loss at 737 nm (emission wavelength of silicon vacancy centers in diamond). As shown in figure 1a, the effective permittivity of the optimized metamaterial approaches zero at the design wavelength, indicating an effective refractive index near zero and corresponding with a spike in the effective impedance.

4. Modeling Power and Decay Rate

4.1 Power Enhancement

To quantify the superradiant enhancement in this coherent system, we normalize the radiated power to the emission of incoherent scatterers (Figure 2c). There is no cooperative enhancement for dipoles in homogeneous diamond due to the random position of the dipoles across a wide area. However, the ENZ metamaterial provides radiant enhancement that increases linearly with the number of emitters. Even for large arrays (wider than 20λ), the radiated power is improved by over an order of magnitude.

The power scaling for the bulk diamond scales as $N$, while the ENZ metamaterial scales as $N^2$. The metamaterial arrays approach closer to this limit as the array gets larger. For larger arrays, (figure 1d), the ENZ moves to a lower index closer to the band edge in order to maintain the lowest-order supermode. For epsilon near-zero metamaterials with a non-zero magnetic permeability, the impedance of the metamaterial increases. This increases the metamaterial’s quality factor as light is less likely to radiate out in the plane of the material due to the large impedance difference with free space. Thus, diamond ENZ metamaterials achieve superradiant enhancement in densely populated emitters distributed over mesoscopic areas.

4.2 Decay Rate Enhancement

Another key signature of superradiance we must numerically characterize is sustained decay rate enhancement at inter-dipole distances greater than a single wavelength. While we can analytically calculate decay rate enhancement using either Fermi’s Golden Rule for two atoms or employ the master equation for a system of many atoms, in simulations we need to calculate the dyadic Greens tensor to generate the decay rate elements in a many body system [4]. Figure 2a shows the ratio of enhancement for two dipoles compared with the single emitter decay rate for both the metamaterial design and a theoretical material with the same index of refraction of 0.02.

For a many-body system of many emitters calculating the exact decay rate becomes exponentially more complex, however we can calculate the ratio of enhancement of the imaginary component of the electric field enhancement for an ensemble of many emitters compared with the decay rate of a single emitter in the same material. Figure 2c and 2d demonstrate this enhancement in the ENZ metamaterial and a theoretical material with the same effective medium properties. This greatly exceeds the enhancement in bulk diamond, which only matches that of the metamaterial at very small inter-emitter distances (figure 2b).

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References

Dispersion engineering for an ultraviolet frequency comb

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Abstract

Anomalous dispersion engineering in the ultraviolet (UV) spectrum is used for efficient bright soliton-based optical frequency comb generation. We have overcome normal dispersion in a III-Nitride platform to create a wideband Kerr frequency comb, with a free spectral range of 400 GHz, centered at 442 nm, to ensure that the Raman gain does not compete with the four-wave mixing gain. This paves the way for applications of fine UV spectral lines in quantum computing, metrology, optical clocks, inertial navigation and secure communication technologies.

1. Introduction

In this work, we report on a systematic approach to dispersion engineering in the UV region of the electromagnetic spectrum to overcome normal dispersion in materials conventionally used for UV optics, namely III-Nitrides. In particular, for realizing this, it is important that the cold cavity has anomalous dispersion to compensate the Kerr-nonlinearity dispersion of the resonator once it is driven with an input laser. For the infrared (IR) and visible regions of the spectrum, there are a variety of material platforms, such as $Si_3N_4$ and $LiNbO_3$, that permit high quality (Q) factors in single and coupled resonators. However, coupled resonators with high Q factors are difficult to achieve in materials working in the UV end of the spectrum due to high material loss and increased scattering from side walls. Dispersion engineering often invokes geometrical modifications to the materials to create high-Q resonators, that test the limits of even current fabrication technologies. Instead, our proposed approach to dispersion engineering is based on a heterostructure supermode with an avoided crossing, which upon coherent and optimized coupling, suppresses the strong normal material dispersion.

2. Theoretical considerations

Consider two waveguides with intrinsic propagation constants $\beta_1$ and $\beta_2$ in close proximity such that there results appreciable co-directional coupling with strength $\kappa = \sqrt{\kappa_{12}^2} = |\kappa_{12}|$. It is well known that such a structure exhibits a supermode with propagation constant

$$\beta = \frac{1}{2}(\beta_1 + \beta_2) - \sqrt{\frac{1}{4}(\beta_1 - \beta_2)^2 + \kappa^2}$$

and an odd transverse mode profile. The corresponding group velocity is given by $1/\nu_g = d\beta/d\omega$, and defining an effective refractive index through $\beta = (\omega/c) n_{\text{eff}}$ where $c$ is the vacuum speed of light, the group velocity dispersion parameter of this supermode can be computed via $D_\lambda = -(\lambda/c) d^2 n_{\text{eff}}/d\lambda^2$, where we switched from angular frequency, $\omega$ to wavelength, $\lambda = \frac{2\pi}{\omega}$, as is conventionally done. This parameter gives the combined material and waveguide dispersion of the hybrid structure. By controlling the geometric parameters of the structure, one can (i) tailor the wavelength $\lambda_0$ of the avoided-crossing point where the original constants $\beta_1$ and $\beta_2$ intersect, and (ii) suppress the normal material dispersion by arranging a strong enough local curvature in the dispersion profile to achieve $D_\lambda > 0$ over a wide band centered at $\lambda_0$. This forms the central basis of our customizable UV frequency comb generation.

3. Numerical simulations

To validate our hypothesis, we have chosen the AlGaN ternary-quaternary material system, since it is one of the ideal materials for UV fabrication [1]. This platform provides a path toward tuning the optical properties by adjusting the mole fraction of their constituent elements, while providing a large bandgap and an appreciable nonlinear optical coefficient [1]. Such a confluence of properties makes it an ideal candidate for ultrashort pulse generation at the UV wavelengths—a prerequisite for combs.

A hybrid micro-ring resonator was designed using III-Nitride family materials, the details of which will be presented in an upcoming journal paper. The propagation coefficients of the whispering-gallery modes of the resonator were then computed using the Wave Optics module of COMSOL Multiphysics finite-element analysis software. Figure 1 shows the simulated dispersion coefficient, which is positive near the target wavelength (442 nm).

The generation of a bright-soliton Kerr comb in this resonator was simulated by solving the Lugiato–Lefever equation in Matlab [2]. The resulting UV frequency comb spectrum is shown in Figure 2.
Figure 1: Dispersion coefficient (solid blue) and refractive index (solid red) for our design, showing anomalous dispersion; for AlN (dashed) and GaN (dotted) showing normal dispersion.

Figure 2: Designed UV frequency comb centered at 442 nm, with a free spectral range of 400 GHz, generating a bright soliton with spectral width of more than 75 nm at the –70 dB window, strongly overlapping with the Yb transitions.

4. Application to an optical clock

Frequency standards play a very important role in both fundamental science and applications relating to position, navigation and timing (PNT). Optical clocks are becoming the de-facto standard for compact portable precise timekeeping due to their mature technologies and ease of handling. Of particular interest is the $^{171}$Yb$^+$ ion. The energy diagram, shown in Figure 3, permits the creation of relevant optical standards based on two transitions (i) $^2S_{1/2}(F=0)$ to $^2D_{3/2}(F=2)$ quadrupole transitions with a central wavelength of 436 nm and a natural linewidth of 3.1 Hz, and (ii) the $^2S_{1/2}(F=0)$ to $^2F_{7/2}(F=3)$ octupole transition at 467 nm with a natural lifetime of several years [3].

As demonstrated in the previous section, our approach to anomalous dispersion engineering enables one to design a bright-soliton Kerr comb in the UV part of the spectrum where the III-Nitride host materials are normally dispersive. Therefore, an integrated optoelectronic on-chip configuration of controllable source of laser lines at the appropriate UV wavelengths can be envisioned for optical clock and metrology applications, as well as for ion-based quantum computing in a photonic integrated circuit.

5. Conclusions

We have designed a UV frequency comb based on the bright Kerr soliton and anomalous dispersion engineering, with a wide number of applications in the PNT and quantum science and metrology domains.

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Optical Magnetism in a Quantum System without Metamaterials

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Abstract

We propose how to synthesize optically active magnetism without metamaterials using quantum-mechanical electric dipole transitions of naturally occurring atoms. We extend the method for toroidal dipoles and anapoles, and a physical realization of a quantum Huygens’ surface that allows for extreme wavefront engineering even at a single photon level. Examples of focusing and steering light, and generations of entangled quantum superposition states with additional photons are provided.

1. Introduction

Optical magnetic dipole transitions in natural media typically are very weak to the extent that magnetic susceptibility at optical frequencies has generally been considered a meaningless concept [1]. The quest for artificial materials with a strong magnetic, as well as electric, response at optical frequencies, has fuelled the rich and rapidly expanding field of metamaterials and thin 2D metasurfaces. Performances of metamaterials at optical frequencies, however, has been limited, and a demand for systems operating at quantum regime would be crucial for rapidly developing quantum technologies, e.g., in sensing and in quantum information processing.

Here we show that strong light-mediated interactions between cold atoms in planar arrays can be designed to synthesize collective radiative excitations that exhibit strong electric and magnetic optical responses [2]. The system has considerable advances over artificial fabricated materials because of the absence of dissipative losses due to absorption and the possibility to reach the quantum regime in the optical manipulation and control. We propose methods for synthesizing a collective excitation of magnetic dipoles and demonstrate how this can be extended to more complex structures such as toroidal dipoles and anapoles [3]. By means of combining the generated magnetic and electric dipolar resonances we show how to construct a quantum-photonic Huygens’ surface of atoms [2]. Huygens’ principle then states that an arbitrary wavefront can be constructed by an ideal physical realization of a Huygens’ surface, therefore achieving extreme optical manipulation. We demonstrate the operation the Huygens’ surface by an ultrathin quantum-atomic lens, focusing the light, by optical beam steering, and by generating orbital angular momentum [4]. The different operations may also be performed as entangled quantum superposition states, where, e.g., the reflected and transmitted light is entangled with a separate photon interacting with the atomic surface.

2. Optical magnetism and toroidal dipoles

Atomic physics technology provides a variety of approaches for trapping closely spaced atoms in arrays with single-site control and unit occupancy per site. The first measurements of the transmitted light through an optical lattice of atoms have now been performed that demonstrate subradiant resonance narrowing where the entire lattice responds as a coherent collective entity. We engineer the spatially extended collective excitation eigenmodes of a large...
array by designing the light-mediated interactions between the atoms in terms of the symmetries of an individual unit cell at each site that forms the lattice [2]. Radiative interactions between atoms lead to collective eigenmodes of the entire array which behave as an effective lattice of unit cells, each with radiative properties determined by specific multipole moments. In Fig. 1(a) We show the excitation of a collective mode in a single layer of atoms that corresponds to an array of magnetic dipoles, one in each unit cell. This is possible, since an isolated square has a collective excitation eigenmode with the dipoles oriented tangentially to the center of the square.

We now turn to the design and preparation of a collective toroidal dipole [3]. The toroidal dipole, as illustrated in the inset of Fig. 1(c), consists of a poloidal electric current wound around a torus, such that magnetic dipoles form a closed loop, reminiscent of vortex current, pointing along a ring around the center of the torus. We approximate this geometry using squares of four atoms [see Fig. 1(c)]. Each square generates a magnetic dipole, as explained before. Arranging several of these squares in a circle, with each aligned perpendicular to the circumference, leads to the magnetic dipole moments winding around the center, as illustrated in the inset, creating a toroidal dipole pointing in the $x$ direction. The system remains point-like, and corrections beyond the long-wavelength approximation are negligible. In an anapole, a nonradiating, yet oscillating charge-current configuration, the far-field radiation of a toroidal dipole is identically canceled by an electric dipole [Fig. 1(d)].

3. Quantum Huygens’ surface

We show how to utilize the combination of electric and magnetic dipoles to prepare a Huygens’ surface [2]. Huygens’ principle states each point on a propagating wave acts as a source of secondary spherical waves which interfere to produce the subsequent wavefront. We superpose the collective electric-dipole and magnetic-dipole excitations to form a nearly reflectionless Huygens’ surface that controls the phase of the transmitted light to engineer its wavefront. While electric and magnetic dipoles both scatter light forwards and backwards with equal amplitude, a crossed electric and magnetic dipole can lead to destructive interference in the backward direction and constructive interference in the forward direction, providing a physical realization of Huygens’ fictitious sources.

To form an effective Huygens’ surface of crossed electric and magnetic dipoles we consider a geometry of Fig. 1(b). The local phase variation of the transmitted light is controlled by modifying the the level shifts of the atoms. In Fig. 2 we show the focusing and beam steering of an incident beam by an atomic surface [4]. We also illustrate the generation of orbital angular momentum of light form a light source with a vanishing angular momentum. For atomic systems the superposition of differently transformed photons can be also controlled by light itself, forming quantum entanglement. This is illustrated by controlling the lattice parameters by an external quantum state of a photon.

4. Conclusions

We have shown how to harness strong light-matter interactions in subwavelength atomic arrays to engineer a collective optical magnetic response, and demonstrated how these can be further superposed to form toroidal and anapole excitations. We use this optical magnetism to create a reflectionless Huygens’ surface which allows for arbitrary wavefront shaping of light.

References


Integration of nitrogen-vacancy center into an one-dimensional photonic crystal cavity

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Abstract

Photonic crystal cavities based on on-substrate tantalum pentoxide waveguides are optimised for coupling to nitrogen vacancy centers in nanodiamond using 3D-FDTD simulations. Coupling conditions depending on the position and size of the nanodiamonds are studied. Antibunching of the photoluminescence signal of an integrated nitrogen-vacancy center in nanodiamond coupled to a 1D photonic crystal cavity is observed experimentally.

1. Introduction

The integration of nanosized quantum emitters remains a major challenge for the realisation of quantum information technologies. To achieve an efficient integration of the emitter, one requires an interface between photonic circuit and emitter, which combines high coupling strengths with low losses. A commonly known approach is to enhance the emitters spontaneous emission rate via the Purcell effect by coupling it to a resonant cavity. Depending on the exact properties of the emitter, there is a vast range of available systems like slot waveguides, plasmonic nanocavities, fiber-based cavities and photonic crystal (PhC) cavities. Here, our goal is the efficient integration of nitrogen-vacancy (NV-) centers in nanodiamond into one-dimensional PhC cavities. Such cavities combine low losses with a small device footprint sufficient for scalable applications. We perform 3D-FDTD simulations to optimise the cavity geometry and to find optimal coupling conditions for the integration of the NV-centers. Based on our results, we perform experiments to integrate NV-centers into a PhC cavity and we are able to measure antibunching of the integrated photoluminescence of the quantum-emitter.

Because the relevant part of the NV-centers emission spectrum lies within the visible wavelength regime, we choose tantalum pentoxide $\text{T}_2\text{O}_5$ as a transparent dielectric waveguide material. Furthermore, to enable compatibility with modern nanofabrication processes, we create the 1D PhC cavities directly on-substrate. While this makes the realisation of the cavity more difficult, it makes our approach sufficient for scaling it up to multiple devices. Besides this, it also enables efficient placement of the NV-centers as verified by our results.

2. Simulation results

Our results in this section are based on 3D-FDTD and eigenfrequency simulations. We start by optimising the band structure of a periodic on-substrate PhC. The effect of the substrate requires a number of significant parameter changes compared to a free-standing PhC cavity, mainly a reduction of the distance between neighboring air holes and an increase of the waveguide width. The PhC nanobeam cavity is created using a deterministic design approach. The dielectric system as well as the

![Figure 1](image-url)  

Figure 1: a) Electric field profile of the resonant cavity mode including dielectric structure (white lines). b) Quality factor over mode volume ($Q/V$) ratio and for two positions within the central air hole (yellow square in a)) and hole radii $r$. The dashed line corresponds to the unperturbed cavity. c) Field profile in the cavity center and normalised electric field profile along line through cavity center. d) Schematics of the two positions of the diamond sphere.
electric field mode profile of the resonant mode is shown in Fig.1a). A zoom-in at the cavity region as well as a field profile across the middle of the cavity is shown in Fig.1c). In this design approach, the hole distances and radii are constant throughout the whole structure. The cavity is created by quadratically increasing (tapering) the waveguide width around a defect center. We follow the optimisation strategies described in [1].

Our goal is to achieve optimal coupling conditions for the NV-centers in nanodiamond. The placement of one or multiple nanodiamonds around the cavity center creates a perturbation of the geometry and is thus an important aspect for the coupling conditions. To take this into account we analyse the cavity properties, including a diamond nanosphere in two different positions around the defect center in our simulations (schematic pictures in Fig.1.d)) [2]. The main contributions to the Purcell enhancement of the emitters spontaneous emission rate are the relative electric field strength at the position of the emitter, as well as the quality factor over mode volume \( Q/V \) ratio of the resonant mode. Based on our optimised cavity structure, we include diamond spheres with radii \( r = 15 \text{ nm}, 25 \text{ nm} \) and \( 35 \text{ nm} \) in those two positions mimicking a cluster of nanodiamonds hosting NV-centers. In Fig.1c) we show the distribution of the electric field profile around the cavity center. The field strength becomes maximal around position 2 and is significantly larger compared to the central position 1. In all cases, we find a decrease of the mode volume \( V \) as well as the quality factor \( Q \) as a result of the perturbation. But while we see a decrease of the \( Q/V \) ratio compared to the unperturbed case for positions 1, the decrease of \( V \) overcompensates the decrease of \( Q \) for position 2, resulting in an increase of \( Q/V \) (see Fig.1b)). This observation combined with the higher relative electric field strength validates position 2 as the optimal position for coupling.

3. Experimental results

Following our simulation results, we place an ensemble of nanodiamonds within the central air hole of the cavity as depicted in the SEM image in Fig.2b). The setup for the integrated measurements is depicted in Fig.2a). The fabricated device is connected to a 532 nm laser, a spectrometer and a 50:50 beamsplitter following two single photon avalanche diodes (SPADs) via ports of a linear optical fiber array. We were able to perform integrated anti-bunching measurements of the NV-centers photoluminescence transmitted into the \( \text{Ta}_2\text{O}_5 \) waveguide. (Inset: SEM of central cavity region including nanodiamonds in the central air hole).

3D-FDTD simulations. Based on the optimised geometry, we analysed the effect of introducing nanodiamond spheres of different sizes and in different positions the defect center to achieve optimal coupling conditions. We found a significant influence of the exact sphere position on the \( Q/V \) ratio, as well as the relative electric field strength. For our cavity design, we found the edge of the central air hole to be the optimal position. Based on the final parameter set, we fabricated a cavity and placed nanodiamonds around the optimal position. Antibunching measurements of the integrated quantum emitter closed clear signature of a single photon emitter. Our results validate the suitability of our approach for quantum technologies with the possibility to scale it up to multiple devices.

4. Conclusions

We have optimised an on-substrate 1D PhC nanobeam cavity for the integration of NV-centers in nanodiamond using

![Figure 2: a) Setup for integrated antibunching measurements. Laser, spectrometer and Single photon avalanche diodes (SPADs) are connected to the device via ports (1-4) of an linear optical fiber array. b) Second order autocorrelation function \( g^{(2)} \) of the NV-centers photoluminescence transmitted into the \( \text{Ta}_2\text{O}_5 \) waveguide. (Inset: SEM of central cavity region including nanodiamonds in the central air hole).](image)

Acknowledgement

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References


Lamb-Dicke Confinement of Cold Atoms in Ferris Wheels.

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Laser beams with optical vortices has given new opportunities to the field of mechanical effects of light on atoms, namely optical cooling and trapping thanks to two important properties: a) the quantized photon orbital momentum along their propagation axis and b) their cylindrically symmetric intensity profile on a plane transverse to their propagation direction [1]. The interference of two co-propagating Laguerre-Gaussian (LG) beams having opposite winding numbers (i.e. \( \ell_1 = -\ell_2 = \ell \)) generates the so called optical Ferris wheel light field [2]. This coherent light field is actually a cylindrical lattice characterized by a pedal-like intensity structure with \( 2\ell \) bright regions.

In applications such as the Doppler-free spectroscopy with trapped cold atoms we need to suppress the recoil effect which accompanies the absorption/emission of a photon by the atom. This suppression is possible if the particle is confined in a region of space with dimensions smaller than the wavelength of the trapping light field. This is the famous Lamb-Dicke limit [3]. In theory and experiment it suffices to consider \( \Delta x, \Delta y, \Delta z < 0.1\lambda \). Such conditions have been observed in optical dipole traps and in optical lattices. [4-8].

The last years there are several proposals on doing physics with cold atoms trapped in a Ferris light field and a prerequisite condition is the strong confinement of atoms in it [9-13]. In our work we investigate the possibility of reaching the Lamb-Dicke limit when a cold Cs atom is trapped inside a far-off resonant Ferris wheel light field created a CO2 laser operating at a wavelength of 10.6 microns for various values of the power and beam waist of the involved LG beams.

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The rms position, in the (a) x-direction, (b) y-direction, and (c) z-direction, of a trapped Cs atom in a Ferris light field ($\ell = 1$) created by a CO$_2$ laser of of wavelength $\lambda = 10.6 \mu$m as a function of power and beam waist. The rms position and the beam waist are given in wavelength units.
Acoustic and seismic metamaterials
Multiple Scattering Theory in the study of Non-Hermitian Sonic Second Order Topological Insulators

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Abstract

Topological insulators with unique edge states have been broadly studied in the fields of condensed matter physics and classical systems such as photonics, acoustics [1] and mechanics. Recently, the concept of TIs has been generalized to higher-order topological insulators (HOTIs), a family of topological phases of matter that obey an extended topological bulk-boundary correspondence principle. HOTIs were mainly focused on electronic materials, but new numerical and experimental researches have been carried out in photonic [2, 3, 4] and sonic crystals (SC) [5, 6]. Here, we make use of the Multiple Scattering Theory in order to calculate the topological corner states of both Hermitian and Non-Hermitian Sonic Second Order Topological Insulators. Our findings reveal that the sound is trapped in the corners of the Concentric Square Crystal considered, which is based on an inner SC made up of a topological non-trivial region enclosed by a topological trivial region. Besides, this semi-analytical approach allows us to compute the spectral dependence of corner states in the presence of defects, illustrating the limits of the topological resilience of these confined non-Hermitian acoustic states. Based on that, we foresee new applications in the field such as sonic energy focusing or new acoustic devices that allow us to control the sound propagation in non-Hermitian systems [7].

Acknowledgement

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References

Numerical and conceptual design of vibroacoustic metamaterial solutions for structural vibration reduction in launcher components

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Abstract

This work deals with numerical and conceptual design of vibroacoustic metamaterial solutions for structural vibration reduction in launcher components. The adjustable and compact design of vibroacoustic metamaterials based on a local resonance effect leads to an attractive and flexible solution especially for lightweight thin-walled structures in space industry. An inverse unit cell modelling approach is used to for the numerical design of a demonstrator including multiple tuned vibration absorbers (TVA).

1. Introduction

To achieve the ambitious requirements for lightweight and cost efficient launchers, the development of new materials and multi-functional structures as well as of innovative manufacturing technologies are essential. Composite materials (e.g. carbon fiber reinforced polymers) enable major mass savings for launcher components, though they lead to high vibration amplitudes. Novel lightweight materials and structures have to retain robust dynamic behavior to keep sensible equipment and fair safe. Vibroacoustic metamaterials represent a promising lightweight solution for noise and vibration problems in many engineering applications. Multiple analytical, numerical and experimental investigations have been performed in the last two decades to explain the working principles of the metamaterial concept [1, 2]. For application in aerospace industry Langfeldt [3] numerically designed and experimentally validated a membrane-type acoustic metamaterial noise shield for an aircraft fuselage. In this contribution concepts for metamaterial solutions in launcher components, such as the cylindrical inter stage in Fig. 1 (a), are being considered. The main goal is to investigate the influence of feasible solutions and their effect on the dynamic behavior of launcher components. For this purpose, multiple resonators on a subwavelength scale have been introduced to a conceptual demonstrator of a cylindrical stage component made of aluminum shown in Fig. 1 (b).

2. Design of demonstrators

Due to demonstrator down-scaling critical Eigenmodes are shifted to higher frequencies. Thus, the targeted frequency range for the stopband is around 1200 Hz.

2.1. Unit cell modelling approach

To determine the driving parameters for the metamaterial design wave propagation in an infinite long pipe is investigated through application of Bloch’s Theorem [4] to a cylindrical unit cell model [5,6]. By using fixed integer values for the circumferential wave number \( k_\phi \), the axial propagation number \( \mu \), indicating amplitude and phase change per unit cell, can be analyzed. The stopband is predicted using an inverse approach resulting in pure imaginary propagation number \( \mu \). Discretization of the unit cell model is done using the Finite Element Method (FE). Fig. 2 shows the ring deformation for beam bending \( (k_\phi = 1) \) and lobar \( (k_\phi \geq 2) \) modes (a) and compares the dispersion relation in bare pipe and metamaterial pipe (b).
Depending on \( k_d \) the metamaterial pipe shows stop band behavior from 1149 to 1230 Hz up to 1133 to 1405 Hz.

![Image](image1.png)

Figure 2: Deformation of cross section (a) and dispersion relation for bare pipe (b) and metamaterial pipe (c)

### 2.2. Numerical investigations of the finite structures

Harmonic response analysis are performed on FE-models of a bare pipe and a metamaterial pipe including 100 TVA with 20% overall relative additional mass. The frequency response function (FRF) of the root mean square (RMS) radial displacement under radial force excitation can validate the predicted stop band (red). For 2% TVA damping an improved dynamic behavior can be seen from about 900 to 1400 Hz. Based on the investigations with ideal discrete TVA conceptual designs of the unit cell can be developed.

![Image](image2.png)

Figure 3: FRF for RMS Radial Acceleration of bare pipe and metamaterial pipe and predicted stop band

### 2.3. Conceptual design

For the use case of the rocket upper stage, different concepts on different detail level have been developed and numerically investigated. Fig. 5 shows two potential designs for the use case of the rocket upper stage. The first concept implies the realization of local resonators by locally removing the material (milling). The second concept considers inclusion of local resonators as purely Add-on elements, thus without major influences on the strength and stiffness of the carrying structure.

![Image](image3.png)

Figure 4: Selected concepts for an application in launcher upper stage

### 3. Outlook

After a detailed simulation investigation and evaluation of all concepts, the most suitable concept will be realized experimentally. The main objective of experimental investigation is to compare the numerically predicted stopband behavior with the real. The modeling parameters as material properties, damping and resonator geometry will be adjusted and updated in the simulation models. The final built cylindrical demonstrator with the metamaterial solution will show the potential of the usage of vibroacoustic metamaterials in space applications.

### 4. Conclusions

The numerical and conceptual design of vibroacoustic metamaterial solutions for launcher components has been performed on a down-scaled demonstrator. Concepts for application in a launcher upper stage could be developed based on unit cell model stop band prediction.

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### References


Design and Manufacturing of Monolithic Mechanical Metastructure with Ultrawide Bandgap for Low Frequency Vibration and Noise Control

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Abstract
The all direction vibration and noise control by novel monolithic metastructures have received considerable research attention in the vibroacoustic community to solve multiple vibration and noise related engineering problems. This new class of acoustic metamaterial has grasped strong root in this research community for its versatile dynamic properties and wave manipulation characteristics exhibited by single unit cell structure. The advancements in numerical computation codes and advanced additive manufacturing technology provide other favorable avenues for breakthrough research in vibration and noise control technology. In that context, the present study proposes a novel 3-D monolithic mechanical metastructure with capability to induce ultrawide three-dimensional bandgap with relative bandwidth or gap-to-mid-gap ratio 171.5%. The bandgap is induced and discussed by principle of mode separation that utilizes the locally resonant global and local modes to open ultrawide bandgap. The proposed metastructure comprises of thin elastic beams connected orthogonally with rigid spherical masses. The axial compression mode by complete unit cell structure and the flexural stiffness of supporting elastic beams are manipulated to generate low frequency extremely wide bandgap. A monoatomic mass-spring chain analytical model is developed to obtain and compare the acoustic mode frequency responsible for initiating the bandgap with numerical wave dispersion study. The wave attenuation inside the bandgap frequencies are demonstrated by developing finite array model and performing numerical frequency response study through two different commercial FEA codes. The analytical and numerical findings are corroborated through experiment test on the 3-D printed prototype. An excellent agreement between numerical and experimental findings are obtained. The simple structural configuration, monolithic design and all direction wave control strategy may find potential industrial and infrastructural applications where all direction wave control is desirable.

1. Introduction
The technological advancements of present and future technologies are relying on safe, sustainable, efficient and environmentally friendly technologies. Radically new industrial and infrastructural techniques, transportation and energy production sectors have substantially modified the urban and interurban vibrations and acoustic landscapes. Vibrations and noise control are among the essential and demanding field of research. Breakthrough technologies and novel smart approaches to cater these challenges are of utmost importance. The recent surge in metamaterial studies and fascinating findings are testimony to the fact that the idea of metamaterial is no longer limited to pure theoretical concepts. In addition, the peculiar dynamic characteristics offered by these synthetic designs make it a potential candidate for vibration and noise control. These metamaterial findings are a prerequisite to advancements in computational approaches, improved numerical codes and additive manufacturing technology for manufacturing solid structures at any length that were once imagined unmanufacturable. When combined, this multi-disciplinary research provides a new platform for the design and application of novel metastructures to control vibration and noises over an ultrawide frequency range.

The present study is related to the novel design of monolithic 3D mechanical metastructure and to envisage the wave attenuation by the proposed structure over ultrawide frequency region. Further details about analytical modelling, numerical simulations and experimental setup can be found in Muhammad and Lim [5].

2. Numerical Results and Discussion
The opulent topology for the unit cell structure and schematic diagram for the finite array is shown in Figure 1. The lattice constant of the unit cell structure is \( a=50 \) mm and all other geometric parameters are presented with reference to it. A detailed geometric parameters are discussed in Muhammad and Lim [5]. The proposed metastructure consists of two parts (i) rigid spherical masses supported by (ii) orthogonal thin elastic beams. This model can be replicated to one-dimensional monoatomic mass-spring chain. We calculated the acoustic mode frequency responsible for opening the bandgap. The analytical frequency obtained is

\[
f = \frac{2}{2\pi} \sqrt{\frac{k}{m}} = 1174 \text{Hz}.
\]

A comparison with numerical results showed percentage error of 8-9%. The numerical study is conducted by employing two different finite element code COMSOL Multiphysics 5.4® and ANSYS workbench R1 2020®. Further details about numerical and analytical model is given by Muhammad and Lim [5].
The numerical wave dispersion study revealed the presence of bandgap ranging from 1292.5 Hz to 16875 Hz corresponding to opening (global resonant mode) and closing (local resonant mode) bounding edges respectively. As shown in Figure 1, a finite array of supercell structure is constructed and frequency response study is performed. The harmonic excitation force is applied at the left edge and response in the form of displacement fields are recorded at the right end. The wave transmission curve showed presence of ultrawide bandgap covering broadband frequency region. The effect of material damping on the wave transmission curve is also taken into consideration. Material damping flattened the wave transmission curve and stretch the vibration attenuation region beyond the closing bounding edge [6, 7]. To corroborate the numerical findings, 3D printer OBJET30 Stratasys Ltd is used to manufacture the 3-D printed prototype, as shown in Figure 1. We performed low amplitude vibration test to envisage the real-time vibration attenuation over ultrawide frequency range. A good agreement between numerical and experimental results are observed although some discrepancy between reported results does exist that is explained in Muhammad and Lim[5].

3. Conclusions

A novel engineered metastructure unit cell structure with capability to generate low frequency three-dimensional bandgap with relative bandwidth 171.5% is proposed and investigated. By numerical wave dispersion study, the presence of ultrawide bandgap is investigated and vibration modes corresponding to opening and closing bounding edges are presented and their role in the bandgap generation mechanism is discussed. The vibration attenuation inside the bandgap frequency range is witnessed by performing frequency response study by two different finite element commercial codes COMSOL Multiphysics and ANSYS workbench. The numerical findings are further corroborated by constructing 3D printed prototype and performing low amplitude vibration test. Both numerical and experimental results revealed the presence of low frequency ultrawide vibration attenuation zone spread over broadband frequency range. The simple structural configuration, monolithic design approach supported by rigorous numerical and experimental findings make the proposed metastructure a viable solution to attenuate vibration and noises at a wide range of frequency. Such novel mechanical design can be of interest for elastic wave manipulation and underwater acoustic applications where all three directions vibration control are desirable.

References


Figure 1. Schematic diagram for unit cell structure with finite supercell model. The real time 3D printed prototype is also shown. The experimental setup developed for performing low amplitude vibration test is presented. The numerical and experimental wave transmission curves revealed low frequency ultrawide vibration attenuation spread over broadband frequency range.
Fluid-like Elastic Reflective Metasurface

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Abstract
Elastic mode conversion has been considered as a unique characteristic of elastic waves that cannot be avoided. In this paper, a fluid-like elastic reflective metasurface that can break this coupling is proposed with numerical and experimental supports. In other word, only longitudinal wave is reflected for the obliquely incident longitudinal wave, i.e., the surface behaves as fluid boundary. We believe that our research may provide a new way in elastic metasurface technologies.

1. Introduction
Unlike acoustic or electromagnetic waves, elastic waves have its own unique physics due to the complicated mode-conversion phenomena. Elastic waves have two wave modes – longitudinal and shear waves – and their complicated coupling have been big scientific obstacles in designing various elastic wave devices. Recently, elastic metasurface has opened a new way in elastic wave devices. Elastic metasurface is a thin periodic artificial structure whose thickness is shorter than the wavelength. It has received much attention in recent years due to their exceptional abilities in wave manipulation and versatility in applications, which were almost impossible previously. However, elastic metasurface has been also suffered from the unique nature of elastic waves – the complicated coupling between longitudinal and shear waves.

Due to this issue, there have been various researches on the tailoring of elastic wave modes. Rong et al. [1] presented multifunctional metasurface for simultaneously control of longitudinal and shear wave based on topology optimization. Kim et al. [2] showed that the incident longitudinal wave can be totally converted to reflected shear wave over a broad range of incidence angles by transmodal metasurface. Also, Zheng et al. [3] proposed a non-resonant elastic metasurface which can completely split longitudinal and shear waves in sace with desired propagating directions and minimum losses over a broad frequency range. However, the coupling of longitudinal and shear waves is still big limit in elastic waves. If the coupling between longitudinal and shear waves can be overcome, the boundary of elastic metasurface can be extremely enlarged as in acoustic or electromagnetic metasurfaces.

In this research, we propose an elastic reflective metasurface which can decouple the longitudinal and shear waves at broad incident angle. In general, if longitudinal or shear waves are obliquely incident to elastic boundary, both the longitudinal and shear waves are reflected due to the complicated coupling phenomena. However, in the proposed metasurface, only the longitudinal wave is reflected if longitudinal wave is obliquely incident, i.e., the elastic boundary acts as the fluid boundary. To support our idea, both the numerical and experimental results will be presented.

2. Design method and Result
In order to achieve the fluid-like elastic reflective metasurface, both the longitudinal and shear waves should be considered. First, from the classical elastic wave theory, we evaluated elastic conditions that can provide the fluid-like elastic reflective metasurface for broad incident angle. After that, the actual metasurface is designed. Especially, we designed the metasurface to have extremely high impedance for either the longitudinal or shear waves, which is the key in the fluid-like elastic reflective metasurface.

In the design, we opted for a simple strip because it is one of the most commonly used as a metasurface unit and also very feasible ways to fabricate. To achieve the desired design goal, we utilized the well-known size optimization algorithm, the particle swarm optimization method. Here, the target frequency is set to be 100 kHz, and the base material is considered to be aluminum. We designed two metasurfaces for the shear and longitudinal wave incident cases, respectively.

Based on the design, the wave simulations are carried out by the commercial finite element analysis tool, COMSOL Multiphysics. Fig. 1 shows the simulation results. For all cases, both the longitudinal and shear waves are reflected from the boundary if the proposed metasurface is not installed. However, as can be seen in the below plots in Figs.
Figure 1: Reflected Shear and Longitudinal wave when each mode is incident at 30 degrees. (The upper row is the free end, the lower row is with the metasurface.)

1 (a,b), if the proposed metasurface is installed, only the shear (or longitudinal) wave is reflected for the obliquely incident shear (or longitudinal) wave. In Fig. 1. (a), when shear wave was incident, only shear wave reflected when metasurface is attached. Also, in case of Fig. 1. (b), longitudinal wave was incident and with metasurface, longitudinal wave reflected. In addition, it was shown that the proposed metasurface works well at broad incident angles.

3. Conclusions

In the presentation, fluid-like elastic reflective metasurface which generates only a same elastic mode as a reflected wave for a certain incidence wave mode. Considering that the coupling between longitudinal and shear waves has been critical problem that decrease the performance of various elastic metasurfaces, we believe that our metasurface can further enhance the current efforts on elastic metasurfaces.

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References

3D Metastructure Design for Noise Suppression of Audible Frequency Band

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Abstract

We fabricated a simple acoustic spectrum measurement system for measuring acoustic transmission loss and proposed a new acoustic metastructure that can reduce noise. To validate the performance of the designed system, the previously studied acoustic metastructure was generated and the acoustic transmission loss was measured and compared. In addition, the novel acoustic metastructure was proposed for noise reduction. The simulation results show that the proposed acoustic metastructure has a loss of 67dB at 478Hz and a bandgap of 448-546Hz.

1. Introduction

Recently, various studies on the acoustic metastructure have been performed to reduce noise/vibration generated in daily life \cite{1-3}. There are two methods of implementing acoustic metastructures: phononic crystal technique using Bragg scattering and local resonance. Phononic crystal technique can be implemented as simple periodic structure with holes or additives, but it is mainly used in ultrasonic region because it requires periodic structure similar to wavelength of operating frequency \cite{4}. Therefore, in order to design the acoustic metastructure that operates in the low band, the local resonance technique that can be implemented with the periodic structure smaller than the wavelength is mainly used. This is a resonance characteristic that occurs at a specific frequency based on a periodically arranged structure, and a band gap where sound waves do not exist in a specific frequency band is formed by interference of sound waves and waves radiated back in the structure, thereby reducing noise/vibration \cite{5}. The local resonance design technique uses resonance characteristics that occur at a specific frequency based on a periodically arranged structure. In the design structure, a bandgap in which sound waves do not exist in a specific frequency band is formed by interference of back-radiated waves \cite{5}. There are two ways to measure the performance of the acoustic metastructure. One is to check the resonant frequency by using the Doppler laser vibrometer to change the characteristics of the structure according to the vibration. The other is an acoustic spectrum measurement method that measures the loss of acoustic transmission using a speaker and a microphone in an anechoic chamber. However, the acoustic spectrum measurement method has disadvantages in that cost and space for constructing an anechoic chamber and a large-area acoustic metadata structure for measuring are required. Therefore, in this paper, a simple acoustic measurement system considering the economic feasibility for verifying the performance of the acoustic metastructure that can reduce the noise of low band is verified through the fabrication and measurement of attenuations. In addition, we designed a new acoustic metastructure that is light in weight and can be manufactured with a 3D printer.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{(a) Simplified spectral measurement system (b) Validations of the fabricated measurement system}
\end{figure}

2. Evaluations of acoustic metastructure

The simplified acoustic spectral measurement system shown in Fig. 1a measures the intensity of the real-time generated acoustic signal based on the Raspberry Pi, a single board computer, and can calculate the sound transmission loss(\text{STL}) of the acoustic metastructure through the FFT algorithm. Prefabricated case was constructed using plywood for easy portability, and sound absorbing material was attached to the wall to reduce reflection of the case and sound signal. In order to verify the performance of the fabricated simple acoustic spectral measurement system, the acoustic metadata structure suggested in the previous study \cite{3} was re-fabricated into a box shape having a size of 12x12x12cm using an FDM-type 3D printer. The media used in the fabrication were ABS filaments with a density of 1050 kg/m\textsuperscript{3}, Young's modulus 2.2 GPa and Poisson's ratio 0.35. As a result of applying the fabricated acoustic meta-structure to the simple acoustic...
spectrum measurement system, it is confirmed that it has the maximum attenuation characteristic of 33.6 dB at 410 Hz as shown in Fig. 1b. To verify the accuracy of the fabricated acoustic spectral measurement system, the intensity of the acoustic signal was measured using the commercial UNIT-T UT353 noise meter. The measured results using the noise meter have a maximum attenuation of 36.4 dB at 400 Hz, and the results are relatively similar to those of the simplified acoustic spectrum measurement system as shown in Fig. 1b.

3. Design of novel acoustic metastructure
As described in the introduction, a new type of acoustic metadata structure is designed as shown in Fig. 2, aiming at noise attenuation around 500 Hz by using local resonator design method. Fig. 2 shows the unit structure of the proposed acoustic meta-structure, which consists of a simple resonant structure in which a rectangular cube is combined with a support. This has various resonance characteristics according to the distance between the support and the hexahedral structure and the size of the hexahedral structure, and thus, the cutoff frequency band can be adjusted by adjusting the thickness of the hexahedral structure and the support.

![Figure 2: Proposed acoustic metastructure](image)

![Figure 3: Simulation results of (a) Bandgap characteristics (b) Acoustic loss of the proposed acoustic metastructure](image)

In order to analyze the performance of the proposed structure, COMSOL Multiphysics software is used, and it is simulated with infinite array structure using Floquet Boundary in consideration of analysis memory and analysis time. As a result of simulating the acoustic loss (Fig. 3a) and dispersion diagram (Fig. 3b) according to the frequency change, it can be seen from Fig. 3b that the maximum attenuation of 67 dB at 478 Hz and the bandgap is shown at 448 ~ 546 Hz.

4. Conclusions
In this paper, we designed the acoustic meta-structure for noise reduction of 500 Hz gold based on the rectangular resonator structure. The simulation confirmed that the designed acoustic meta-structure can block the sound in the 448 ~ 546 Hz band. In addition, in this paper, a simple acoustic spectrum measurement system is fabricated to verify the performance of the proposed structure. The measurement system is capable of measuring and analyzing the strength of the real-time sound signal through the FFT process by receiving the sound signal in the low frequency band. As a result of the measurement, the simulation result and the error of about 21 Hz are generated, but it is confirmed that the performance of the acoustic metastructure can be predicted. In the future, the proposed acoustic metastructure will be manufactured by 3D printing method and the performance of the proposed structure will be verified by using the simplified acoustic spectrum measurement system.

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References
Chiral and hyperbolic metamaterials
Absorption control in epsilon-near-zero hyperbolic metamaterials based on InAs

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Abstract

Here we present the possibility to control the epsilon-near-zero (ENZ) region by properly designing a hyperbolic metamaterial (HMM) based on InAs, which allows for an adjustable absorption in mid-IR. Numerical results show that by increasing thickness of the undoped InAs layers we are able to redshift the absorption by ~14 μm. Also, transition from hyperbolic dispersion type I to ENZ and type II is observed. The designed HMM stack may provide a platform for perfect metamaterial absorbers in mid-IR.

1. Introduction

Epsilon-near-zero (ENZ) behavior was recently demonstrated in metal-dielectric multilayers known as hyperbolic metamaterials (HMMs), which consist of a large number of periodically stacked subwavelength metal-insulator unit cells [1,2]. ENZ conditions occur when the relative permittivity attains near-zero values around a given frequency (plasma frequency) – the real part of the permittivity gets near zero (its imaginary part is small) [3]. Although properties of HMMs present a great opportunity for designing a group of novel nanophotonic devices such as tunable filters, switches, modulators, sensors and many others [4,5], here we focused mainly on the application as a controllable perfect absorber for mid-IR range using InAs as a base for multilayer metastructure.

2. Theoretical model

The relation between the permittivity ε and angular frequency ω of a doped InAs can be modeled using the Drude model:

\[ \varepsilon(\omega) = \varepsilon_\infty \left(1 - \frac{\omega_p^2}{\omega^2 - i \omega \Gamma} \right), \]

\[ \omega_p^2 = \frac{n e^2}{m^* \varepsilon_0 \omega_0}, \]

where \( \varepsilon_\infty \) is the relative permittivity of undoped InAs at low frequency, \( \Gamma \) is the scattering rate, \( \omega_p \) is the plasma frequency of the doped material, \( n \) is the free carrier concentration (assumed to be equal to dopant concentration), \( m^* \) is the effective mass of the free carriers, \( e \) is the elementary charge, \( \varepsilon_0 \) is the permittivity of free space and \( i \) is the imaginary unit.

Considering the permittivity of InAs and n-doped InAs, which can be determined from Equation 1, we designed a stack in the form of a HMM, as depicted in Fig. 1.

Figure 1: Stack model of InAs and n-doped InAs.

The effective medium theory (EMT) was used to describe wave propagation through a HMM stack consisting of \( N \) unit cells. The designed metamaterial is an anisotropic medium with uniaxial dielectric tensor components, \( \varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_\parallel \) and \( \varepsilon_{zz} = \varepsilon_\perp \), which may be approximated as follows [6]:

\[ \varepsilon_\parallel = \frac{\varepsilon_n \varepsilon_d (t_n + t_d)}{t_n \varepsilon_d + t_d \varepsilon_n}, \]

\[ \varepsilon_\perp = \frac{\varepsilon_\parallel}{t_n \varepsilon_d + t_d \varepsilon_\perp}, \]

where \( t_d \) and \( t_n \) are the thickness of InAs and n-doped InAs layers respectively, \( \varepsilon_d \) and \( \varepsilon_n \) are the permittivity of InAs and n-doped InAs respectively.

The analysis of optical properties of the multilayer stack was performed using the transfer matrix method [7], enabling us to obtain complex transmittivity and reflectivity coefficients (\( t \) and \( r \) respectively), and therefore calculate transmittance \( T = |t|^2 \) and reflectance \( R = |r|^2 \) parameters of the structure. Based on this approach it is possible to calculate absorption \( A \) of the HMM as follows [1]:

\[ A = 1 - T - R. \]

3. Results and discussion

The results were obtained for multilayer stack of InAs and n-doped InAs with different dopant concentrations and thicknesses of the layers. Presented in this paper are results of numerical modeling for stack composed of \( N = 20 \) unit cells, undoped InAs permittivity set to constant \( \varepsilon_\infty = 11.56 \), InAs dopant concentration \( n = 1.0 \times 10^{19} \) cm\(^{-3} \) and constant thickness of the n-doped InAs layers \( t_n = 100 \) nm. The
The thickness of the undoped InAs layers changes from \( t_d = 0 \) nm (no undoped InAs layers) up to 500 nm. The relative permittivity of the simulated HMM for \( t_d = 100 \) nm is presented in Fig. 2.

![Relative permittivity of simulated metamaterial.](image1)

Figure 2: Relative permittivity of simulated metamaterial.

In the case presented in Fig. 2 we can observe four different behaviors – elliptic dispersion up to \( \sim 10 \) μm \((\varepsilon_\parallel > 0, \varepsilon_\perp > 0)\), hyperbolic dispersion of type I from \( \sim 10 \) μm to \( \sim 14 \) μm \((\varepsilon_\parallel > 0, \varepsilon_\perp < 0)\), ENZ region \( \sim 14 \) μm \((\varepsilon_\parallel \approx 0, 1/\varepsilon_\perp \approx 0)\), and hyperbolic dispersion of type II starting at \( \sim 14 \) μm \((\varepsilon_\parallel < 0, \varepsilon_\perp > 0)\).

The reflectance and absorption obtained for different thickness of undoped InAs layers \( t_d \) are presented in Fig. 3 and Fig. 4 respectively.

![Reflectance for different thickness of undoped InAs layers.](image2)

Figure 3: Reflectance for different thickness of undoped InAs layers.

![Absorption for different thickness of undoped InAs layers.](image3)

Figure 4: Absorption for different thickness of undoped InAs layers.

The results presented in Fig. 3 confirm the transition to hyperbolic dispersion type II, as the reflectance significantly increases near the transition wavelength (e.g. \( \sim 14 \) μm for \( t_d = 100 \) nm). As shown in Fig. 4 at the same wavelength the absorption is the highest – which confirms presence of ENZ region at this spectral position [1]. Both reflectance curve and absorption band are redshifted with respect to increasing thickness of the undoped InAs layers. By changing the thickness \( t_d \) from 0 nm up to 500 nm we obtain shift of the absorption band from \( \sim 9.5 \) μm to \( \sim 24 \) μm. Also, at the same time the absorption coefficient rises from \( \sim 63\% \) up to \( \sim 97\% \). This provides an insight into a possible control of the absorption band spectral position and effectiveness based on the composition of the HMM.

4. Conclusions

In the presented studies a HMM based on InAs was modeled and studied by means of EMT. The relative permittivity components analysis confirms the presence of ENZ region as well as hyperbolic dispersion regions of type I and type II. It was shown that the region of transition from type I to ENZ and to type II may be controlled e.g. by changing the thickness of undoped InAs layers. At the same time it can be used to tune the absorption band and shift it into longer wavelengths. This type of HMM may be used e.g. as a controlled band absorber for the entire mid-IR.

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References


Active Chiral Metasurfaces via Colloidal Self-Assembly

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Abstract

Active chiral metasurfaces enable continuous on-chip polarization engineering, detection and encoding. Here, we introduce a facile bottom-up approach that produces circular dichroism of up to 11 degrees in the visible-near-infrared spectral region. This pronounced effect surpasses previous colloidal approaches by two orders of magnitude. Furthermore, the presented design of stacked particle chain arrays allows in-situ re-stacking and local compression to tune dynamically all aspects of circular dichroism: sign, magnitude and spectral position.

1. Introduction

Similar to molecular enantiomers, the absence of mirror and inversion symmetry yields chirality in chiral plasmonic metasurfaces. However, the superior light–matter interaction of the latter produces pronounced chiroptical effects like circular dichroism that can be tailored by design. Moreover, the superchiral near-fields of these metal nanostructures enable zepto-molar enantio-selective detection of molecules[1]. At visible and near-infrared wavelengths, complex designs like spirals[2] and layered helices[1] are inevitable to achieve pronounced circular dichroism.

Introducing dynamic polarization control opens intriguing routes for switching photonic circuits and complex structuring of light. To date, only individual aspects of circular dichroism were demonstrated to be tuned in a post-fabrication fashion. Amongst these, the reconfiguration of handedness (sign of circular dichroism) is most challenging in solid-state devices, since it demands geometrical reconfiguration or sophisticated switching mechanisms[3].

Here, we demonstrate a strategy that combines simple fabrication, pronounced chiroptical effects and full control of circular dichroism: sign, magnitude and spectral position. We build on our experience in the cost-efficient colloidal self-assembly of mechano-tunable 2D plasmonic lattices[4,5] to realize stacked particle chain arrays (Fig. 1a). Reversible re-stacking of the two substrates and compression of the elastic matrix enable post-fabrication tunability of circular dichroism. Electromagnetic and mechanical simulations explain the strain-induced spectral shift by an out-of-plane bending of particle chains.

2. Results and discussion

Particle double chain arrays were fabricated via capillarity-assisted particle-assembly[4,6] of 77 ± 2 nm sized gold nanoparticles inside 240 nm wide and 100 nm deep channels (periodicity 365 nm; Fig. 1b). Stacking two as-prepared achiral particle chain arrays yields a chiral arrangement for oblique stacking angles (Fig. 1a). The intrinsic chirality of the nanostructure and strong inter-particle coupling generate pronounced circular dichroism on macroscopic areas, as visible to the bare eye (Fig. 1c). In the region of the stacked chiral bilayer, the magenta fraction of light is absorbed more efficiently for right circularly polarized light (RCP) as compared to left circularly polarized light (LCP). In contrast, the achiral monolayer of chains does not show any polarization-selective absorption.

Figure 1: Stacked chiral metasurface. (a) Scheme of stacking approach. (b) SEM image of assembled gold nanoparticle chains. Scale bar: 1 µm. (c) Circularly polarized photographs of the stacked sample. The (crossed) lines indicate regions of stacked bilayer and monolayer of particle chains, respectively. Scale bar: 0.5 mm.
The circular dichroism was further quantified using spectroscopic ellipsometry. Fig. 2a plots the circular dichroism (CD), which is related to the differential absorbance of LCP and RCP light. Several pronounced CD modes were observed ranging from visible to near-infrared wavelengths. The most pronounced one is located at 1240 nm and reaches 11.3 degrees for a stacking angle of −45° (dark blue curve). The reversible adhesion between the two substrates allows re-stacking at different stacking angles θ (Fig. 2a). That way, the CD magnitude can be tuned continuously. Changing the sign of the stacking angle θ switches the handedness of the chiral arrangement. As expected for intrinsic chirality, the spectra of two such enantiomorphs are inverted, i.e. one enantiomorph absorbs more LCP light at a specific wavelength, whereas the other one absorbs more RCP light.

Taking advantage of the elastic substrate, compressive strain was applied normal to the interface to tune the spectral position of the near-infrared CD modes (Fig. 2b). With increasing compression a ~80 nm blue shift was observed. Mechanical and electromagnetic simulations reveal that strain-induced bending of particle lines causes this pronounced shift. This is illustrated by the scheme in Fig. 2b.

3. Conclusions

Reversibly stacking two self-assembled chain arrays represents a simple and scalable route for metasurfaces whose substantial circularly dichroism can be tuned in all aspects. In particular, the local strain-induced spectral modulation opens possibilities in designing spectral gradients or pixel arrays to realize multi-channel detection and monochromatorless spectroscopy. Furthermore, large volumes of superchiral fields verified by electromagnetic simulations potentially lower the limit of detection in enantio-selective molecular detection.

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References


Switching the Optical Chirality by Magnetic Fields in Magnetoplasmonic Metasurfaces

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Abstract
We report a magneto-optical metasurface device using low loss Ce:YIG thin films for active chiroptical photonic device applications. A far field modulation of the circular dichroism from -0.6° ± 0.2° to +1.9° ± 0.1° at 950 nm wavelength is observed under applied magnetic fields, enabling efficient control of optical chirality both in the far field and near field at the subwavelength scale.

1. Introduction
Chiral symmetry refers to structures which cannot superimpose with its mirror image through translation and rotation operations. Chiral photonic nanosstructures show unique optical properties, such as circular dichroism (CD) and optical rotation (OR), which is potentially useful for chiral molecule sensing applications. Recently, active chiral nanophotonic devices have attracted great research interest, due to their functionality and reconfigurability. Several methods have been reported for tuning the optical chirality, such as using DNA origami,¹² phase-change materials,³⁴ mechanical deformation,⁵ chemical reactions,⁶ and magneto-optical effects.⁷⁸ Among these mechanisms, the active chiroptical devices based on magneto-optical effects has the advantages of high speed, low-power dissipation, and small size. These devices usually rely on the magneto-optical effect of magnetic metals, such as Fe, Co and Ni. However, magnetic metals show weak magneto-optical effect and very high optical loss in optical frequencies, which lead to the CD modulation by magnetic field always much weaker than the structural CD. Therefore, efficient modulation of the optical chirality in optical frequency using magnetic field has not been demonstrated.

2. Magnetoplasmonic chiroptical metasurfaces using Ce:YIG thin films
In this report, we present the continuous tuning of extrinsic chirality in a magneto-optical metasurface using low loss magneto-optical oxides (Ce:YIG).⁹ The device shows one order higher modulation amplitude in the optical chirality both in the near field and far field under applied magnetic field compared to previous reports. Figure 1a shows the schematic of the device. The device consists of Au/ Ce:YIG/YIG/SiO₂/TiN multilayers deposited on a silica substrate. The Au thin film with periodic hole structure on the device surface is fabricated by polystyrene (PS) sphere self-assembly. Although the periodic hole structure is achiral, it will show extrinsic optical chirality for circular polarized light under oblique incidence, due to the asymmetry of near field distribution of the electric fields in the structure. Due to the magneto-optical effect of Ce:YIG layer, we can continuously control the extrinsic chirality by applying magnetic fields. First, we characterize the extrinsic optical chirality by measuring the CD spectrum under zero magnetic field, as shown in figure 1b. The CD value is proportional to the incident angles, which achieves maximum 1.5° at 60° incident angle. We also observe zero CD under normal incidence, confirming its extrinsic nature. The CD peaks red shift to longer wavelength as increasing the incident angle, due to the coupling between the surface plasmon mode and cavity mode excited in Au/Ce:YIG interface and Ce:YIG layer, respectively. After that, we demonstrate the modulation of CD from -0.6° ± 0.2° to +1.9° ± 0.1° at 950 nm wavelength using the magnetic field, as shown in figure 1c. Here, the applied magnetic field is ±3.1 kOe and incident angle is 45°. In figure 1d, we also demonstrate the continuous modulation by magnetic field. In order to visualize the modulation, we fabricate a 2×2 mm "UESTC" pattern using photolithography technique and PS sphere self-assembly, as shown in figure 1e-g. We measure the reflectance RCD (CDR) using the CCD, which is defined as:

\[ RCD = \frac{R_{R_{BCP}}(H) - R_{R_{LCF}}(H)}{R_{R_{BCP}}(H) + R_{R_{LCF}}(H)} \]  

Here the \( R_{R_{BCP}} \) and \( R_{R_{LCF}} \) represent the reflectivity of the right and left circular polarized incident light, respectively. After applying magnetic fields of ±3.1 kOe, we observe obvious RCD sign reversal in the whole image at the metasurface regions indicated by color code changing from yellow (positive RCD) to blue (negative RCD). The CD modulation amplitude reaches 6° in most structural regions, which is comparable to the single point measurement results. This result demonstrates the possibility to fabricate large
scale active chiroptical metasurfaces using magneto-optical materials, which is promising for imaging and sensing applications.

Such active chiroptical devices could be useful for chiroptical sensing applications, we simulated and experimentally characterized chiral sensing performance of our magneto-controllable devices using the intrinsic chiroptical metasurfaces, such as gammadon, nanospirals. For chiral sensing, we use the magnetic field to remove the far-field structural CD and keep the enhancement of near-field optical chirality. Using this strategy, we can achieve high sensitivity as well as high signal to noise ratio for chiral molecule sensing applications.

Figure 1: (a) Schematic of the device. (b) Experimental CD spectra of the metasurface device with different incident angles. (c) The experimental CD spectra under 0 and 3 kOe applied magnetic fields at 45° incidence. (d) The experimental CD spectra for the 45° incidence condition and under applied magnetic fields changing from -3.1 kOe to +3.1 kOe. (e) RCD image without applied magnetic fields. (f) RCD image with out-of-plane applied magnetic field of +3.1 kOe. (g) RCD image with out-of-plane applied magnetic field of -3.1 kOe

3. Conclusions

In summary, we demonstrate switching of the far field optical chirality in magneto-optical metasurfaces using low loss magneto-optical oxide thin films. The far-field CD can switch from $-0.6^\circ \pm 0.2^\circ$ to $+1.9^\circ \pm 0.1^\circ$ under the applied magnetic fields. We also demonstrate large scale magnetic field tunable chiral images. Furthermore, we demonstrate chiral sensing application of such devices. Our results may inspire applications such as chiral sensing and display technologies using active magnetoplasmonic chiroptical metasurfaces.

References


Giant third-harmonic dichroism in all-dielectric chiral metasurfaces based on quasi-bound states in the continuum

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Abstract

We develop a new approach based on quasi-BICs to develop chiral metasurfaces exhibiting nonlinear circular dichroism (up to 99.9\%) and high conversion efficiency. Tuning mode interference allows selective linear and nonlinear circular dichroism.

1. Introduction

The capability to control the optical response of a device by playing on the incident light polarization state is opening the way for many new applications from telecommunications to sensing. In this context, a prominent effect is the circular dichroism (CD), yielding a different response upon illumination with light having opposite spin angular momentum [1]. Although this phenomenon is extremely weak in natural materials, metasurfaces provide unprecedented means to enhance CD. In particular, chiral dielectric structures supporting both electric and magnetic resonances have proven to enhance CD [2]. In comparison to the linear regime, CD in the nonlinear regime (NLCD), e.g. higher harmonic-generation for one circular light polarization with respect to the opposite one, may exhibit a much higher contrast. To date, such investigations of NLCD are still limited to plasmonic structures [3]; however nonlinear metasurfaces based on dielectric materials have the potential to yield high NLCD and superior conversion efficiencies.

In this work we design chiral Si-metasurfaces supporting a high Q-factor (\(>10^5\)) Fano resonance to enhance third harmonic generation (THG) with a conversion efficiency for circularly polarized light up to \(10^{-4}\) W\(^{-2}\). The chiral geometry enables selective excitation of the high-Q mode and high NLCD in THG (up to 99.9\%). Notably, our design allows to engineer the metasurface to either enhance or reduce CD at the pump wavelength.

2. Results and discussion

We use full-vectorial numerical simulations implemented in COMSOL Multiphysics to calculate the eigenmodes and spectral response of the metasurface. The metasurface geometry is depicted in Fig. 1a). The unit cell of period 700 nm contains two Si blocks. Each block has thickness of 214 \(\text{nm}\) and height of 575 nm. One block length, \(L\), is 600 nm, while the other is shorter by a factor \(\alpha=\Delta L/L\) (asymmetry parameter), \(\Delta L\) being the length difference between the two blocks (Fig. 1a). The gap between the blocks is 116 nm. The considered metasurface supports symmetry-protected bound state in the continuum (BIC) at a wavelength of 1610 nm for \(\alpha=0\) [4]. As the asymmetry parameter, \(\alpha\), is increased, the BIC evolves into a finite Q-factor mode that is known as quasi-BIC [4], whose electric field profile in the blocks is displayed in Fig. 1a). In Fig. 1b) we report the wavelength of the eigenmodes as a function of \(\alpha\). The quasi-BIC is shown in blue and its Q-factor as a function of \(\alpha\) is reported in Fig. 1c). As \(\alpha\) approaches 0.25 the Q-factor reaches a local maximum of \(10^5\). This sweet-spot – caused by the presence of an accidental BIC formed due to a simultaneous destructive interference of leakage channels [5] – allows to get a high-Q resonance with a strong potential for enhancing third harmonic generation (THG) in a highly asymmetric unit cell. When \(\alpha\neq0\) the unit cell geometry is chiral and CD is expected in such dielectric structures. This is confirmed from the different reflectivity (\(R\)) spectra of left circularly polarized (LCP) and right circularly polarized (RCP) incident light (Fig 1d). The difference in reflectivity is quantified as \(\Delta RC D= (R_{RCP} - R_{LCP})/(R_{RCP} + R_{LCP})\). The reflectivity spectra for RCP shows a Fano resonance at a wavelength of 1589 nm that corresponds to the quasi-BIC. Conversely, this peak is not visible for LCP illumination. For the metasurface with the \(\alpha=0.25\), we estimate the TH conversion efficiency, defined as \(\eta_{3H}= P_{3H}/P_F\), where \(P_F\) is the light power illuminating the unit cell at the fundamental frequency (FF), whereas \(P_{3H}\) is the TH emitted power. In Fig. 1e) we report \(\eta_{3H}\) as a function of the FF wavelength, in the wavelength range around the quasi-BIC. The dashed and full black curves are obtained when the metasurface is pumped with LCP and RCP, respectively. When the pump is tuned to the quasi-BIC the TH efficiency is enhanced (peak in Fig 1e). This is due to the high Q-factor of the mode and resulting strong pump electric field enhancement within the two blocks. Remarkably, the maximum TH efficiency is 2 orders of magnitude higher for RCP pump with respect to the

\[ \eta_{3H} = \frac{P_{3H}}{P_F} \]
LCP pump. We thus define the nonlinear circular dichroism (NLCD), as
\[
\frac{\eta_{3H}^{RCP} - \eta_{3H}^{LCP}}{\eta_{3H}^{RCP} + \eta_{3H}^{LCP}}.
\]
The NLCD of our metasurface can reach 99.9% around the quasi-BIC wavelength.
Furthermore, in proximity of the quasi-BIC mode where the NLCD is maximum, the CD is mild. Nevertheless, by changing the dimensions of the two blocks it is possible to tune the interference between the modes of the Si blocks to achieve high LCD and the NLCD.

3. Conclusions
We presented and numerically validated a new dielectric nonlinear metasurface for giant nonlinear circular dichroism up to 99.9% and, simultaneously, highly efficient THG (up to \(10^{-2} \text{ W}^2\)). High-Q Fano resonances are engineered based on quasi-BIC mechanisms where the resulting in-plane broken symmetry is chiral. Nonlinear metasurfaces exhibiting dichroism may open the way to the development of new optoelectronic devices for a huge range of new and emerging applications based on spin angular momentum of light such as telecommunications, quantum optics, and biological sensing.

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References
Metamaterial-based devices
Wideband and High-gain Metasurface-Based Circularly Polarized Antenna

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Abstract
A metasurface-based circularly polarized microstrip patch antenna with wide bandwidth and high gain is presented. The antenna structure is a square modified microstrip patch that is sandwiched between a metasurface and the ground plane. The metasurface comprises a 4 × 4 array of square patches, while the radiating microstrip patch has axial ratio (AR) tuning stubs and a cross slot. The microstrip patch and cross slot, in conjunction with the metasurface, generate multiple resonances and AR minimum points that are combined to produce large impedance, AR, and 3-dB gain bandwidths. The antenna with the dimensions of 54 mm × 54 mm × 3.1 mm has a ~10 dB impedance bandwidth of 5.62–11.04 GHz (65.06%), a 3-dB AR bandwidth of 5.64–7.89 GHz (33.25%), and a 3-dB gain bandwidth of 5.17–8.2 GHz (45.32%) with a peak gain of 12.17 dBiC.

1. Introduction
Circularly polarized (CP) antennas are popular in many communication applications due to their merits of flexibility in transceiver orientations for stable signal transmission and reception [1]. In many applications, low-profile and lightweight CP antennas with wide bandwidths and high gains are needed to enhance the system performances [2]. In recent years, microstrip patch antennas have earned prominence in the research and development of compact lightweight CP antennas due to their advantages of low profile, conformal structure, ease of fabrication and integration [3]. However, narrow bandwidth and low gain are the main drawbacks of microstrip patch antennas that limit their applications. Metasurfaces when combined with microstrip patch radiators provide bandwidth and gain enhancements while retaining the low profile of the antenna [3]. In many antenna configurations, the metasurface is placed directly above [4] or under [5] the radiator. Nonetheless, design complexities and high profiles coupled with poor mechanical properties are the main drawbacks of antenna designs using the metasurfaces. On the other hand, the metasurface is directly stacked on the radiator to achieve a low profile with large bandwidth and high gain [6]. In this paper, a wideband and high gain CP microstrip patch antenna incorporated with a 4 × 4 array of square patch metasurfaces is presented. To enhance the narrow bandwidth and low gain of the square microstrip patch, a cross slot was etched on the microstrip patch and sandwiched between the metasurface implemented on a low dielectric foam materials and the ground plane.

2. Antenna Geometry
The geometry of the proposed antenna is shown in Fig. 1. The antenna is composed of a driven patch, foam material (ε=1.06, tanδ=0.0011), a metasurface, and a ground plane. The metasurface is a 4 × 4 array of square patches with periodicity P and space g. The radiating element is a square patch sandwiched between two identical foam materials. The square patch has two slots of lengths L1 and L2 that are oriented diagonally and crossed at the center, while being located at the center. Four L-shaped stubs are added on the patch for AR tuning. An extended strip with tapering is added to the driven patch to improve its impedance matching. The outer conductor of the coaxial line is connected to the ground plane, and the inner conductor of the coaxial line passes through the foam to connect with the extended strip of the radiating patch. The antenna was optimized with the ANSYS HFSS. The optimized antenna design parameters are as follows: P=13.5 mm, g=1.5 mm, W=14.2 mm, L=15 mm, L=9 mm, W=12.0 mm, W=8.7 mm, W=0.7 mm, W=2.1, S=2.3 mm, F=12.7 mm, F=5.1 mm, F=2.2 mm, T=4.5 mm, h=0.0508 mm, and h=1.5 mm.

3. Antenna Performance
The proposed antenna generates multiple resonances in its reflection coefficient and three AR minimum points in an AR profile. Fig. 2 shows the reflection coefficient of the antenna. The proposed antenna produces a |S11| ≤ –10 dB bandwidth in the range of 5.65–10.92 GHz (63.6%). Fig. 3 shows the AR of the antenna. Three AR minimum points are recorded: two from the patch and a third AR minimum point from the metasurface. The 3-dB AR is in the range of 5.65–7.98 GHz (34.1%). Fig. 4 shows the gain of the antenna. The antenna generates a high gain, a wide 3-dB gain bandwidth in the range of 5.17–8.2 GHz (45.32%) and a gain above 10 dBiC within the entire CP bandwidth. The technique applied to achieve high-gain performance utilizes low-dielectric foam materials (ε=1.06). These low dielectric constant materials increase the patch sizes at resonance, and consequently, the radiating areas to effectively enhance the antenna gain.
4. Conclusions

A low-profile, high-gain, and wide bandwidth metasurface-based antenna is presented. The wide bandwidth is obtained using a cross slot on a square modified patch and four AR tuning stubs. The patch is stacked between low-dielectric foams, along with the ground plane and a $4 \times 4$ square patch metasurface array. The proposed antenna generates broadside gain values above 10 dBic throughout the CP bandwidth. Many aforementioned advantages of this antenna increase its utilization in space applications where high gain and wide bandwidth are crucial.

Acknowledgements

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References

Multipolar analysis of random all-dielectric nanoresonator arrays

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Abstract

The optical properties of bottom-up amorphous arrays with stochastic distribution of high-index dielectric antennas stem from an interplay of the single-particle response, mutual coupling and substrate-mediated effects. We develop a theoretical framework that incorporates electric and magnetic dipolar interactions to prove that interparticle coupling even in random arrays is important. These interactions are responsible for density-driven effects such as modification of directional scattering, sensitivity enhancements, or efficient solar harvesting. Our results show how to utilize intra-array coupling to maximize these properties e. g. in refractometric sensing.

1. Introduction

High-index dielectric nanostructures have recently gained significant attention due to exhibiting both a magnetic and an electric response and the possibility of observation of suppressed backscattering when the amplitudes of electric and magnetic dipole are identical [1]. This makes them a suitable choice for Huygens metasurfaces, whose magnetic and electric dipole resonances overlap spectrally. They provide suppressed reflection and near-unity transmittance as well as the capability to tailor the phase of transmitted light leading to the possibility of creating efficient flat analogues of conventional optical devices. The optical properties of these so-called metasurfaces depend on the properties of individual components such as material, size and geometry as well as their spatial distribution, which dictates how radiative coupling between nanoparticles within the array modifies the single particle response. Although modern fabrication methods offer a broad range top-down tools for almost arbitrary nanoresonator geometries and arrangements, still, periodic and random placement is often used. Here, we focus on amorphous arrays of dielectric antennas in which nanoresonators are arranged randomly with a fixed minimal interparticle distance, leading to a short-range order.

2. Film of spherical multipoles framework

A common route towards investigating multipole moments of nanoparticle arrays is the coupled multipole approach in which a set of self-consistent equations for multipole moments is solved and Green propagators are used to calculate scattered fields from respective multipoles. Here we propose to use a self-consistent approach based on T-matrix method [2]. The advantage of using the T-matrix approach is that it can be extended towards substrate-supported arrays [3]. The substrate’s presence then enables electromagnetic coupling between multipoles that cannot couple in a homogeneous environment. We visualize this by showing the coupling matrices in Fig. 1a-b. To show that indeed it is a considerable effect, we exemplify it by comparing substrate-supported array of silicon nanospheres to an array embedded in a homogeneous medium in Fig. 1c-d.

We focus mainly on amorphous arrays of silicon nanodisks. Apart from the ease of fabrication, they also the ability to modify the relative spectral separation between the magnetic and electric resonances by changing the aspect ratio of the resonator.

In the case of infinite periodic nanoparticle arrays, the neighbourhood of each particle is identical. This fact enables one to consider only a single particle excited by external field and scattered fields from the neighbouring nanoparticles. In contrast, if the nanoparticles are distributed randomly, the neighbourhood of each nanoparticle is unique, yet the far-field properties of the disordered array are still well defined. We therefore calculate the average multipole moments of the nanoresonator placed in the infinite amorphous array by considering a single particle excited by external field and the average scattered field from

Figure 1: Optical properties of amorphous array of Si nanospheres with D=200 nm. (a,b) Coupling matrix for 550 nm wavelength and minimal center-to-center (CC) equal to 2.5D. (c,d) Extinction spectra of amorphous array with CC=2.5D and CC=6D compared to the spectra of arrays embedded. Substrate refractive index is 1.45.
an effective film of multipoles described with pair correlation function dependent on statistical properties of the array, i.e. minimal center-to-center distance between particles.

3. Discussion of amorphous arrays in devices

Once the average multipole moments are calculated, it is possible to calculate the total optical cross-section of a nanoresonator in the array. To verify our model, we compare the extinction cross section of a Si nanodisk array with results obtained with a T-matrix method based code, SMUTHI [3]. As presented in Fig. 1, the model provides correct results both in terms of amplitude and resonance wavelength. When the interparticle distance is varied, the optical properties of the array exhibit characteristic oscillatory behaviour showing that nanoparticle separation in amorphous array can be effectively used as a handle to adjust nanoparticle coupling for specific applications. We focus on bulk refractive index sensitivity. It can be obtained from the spectral shift of the selected resonance. We choose the magnetic dipole and assume that the peak shift is monotonous in a narrow \( n_{sd} \) (surrounding refractive index) range, obtaining a mean array sensitivity. We show that radiative coupling can significantly influence sensitivity of the array to bulk refractive index. Radiative coupling depends on the relative phase between incident and scattered field and which in turn is influenced by the wavelength of light in the medium surrounding the particle [4]. We utilize our model to show that even if the single particle sensitivity is zero - which is typically the case for dielectric nanodisks - the radiative coupling can lead to sufficient sensitivity enhancement for practical applications (see Fig. 3). Oscillations of an array sensitivity are centered around a single-resonator value, which shifts for various substrates. Arrays of Si nanodisks of radius \( R = 80 \) nm and height \( H = 160 \) nm are able to achieve best sensitivity of 70 nm/RIU when placed on a substrate with refractive index \( n_{sub} = 2 \).

Acknowledgement

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References

Investigation of electromagnetic coupling between the antenna and split-ring-based metasurface in CMOS technology

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Abstract

In this contribution we investigate the electromagnetic coupling between the 350 GHz resonant antenna and the metasurface constructed from an array of split-ring structures which are monolithically integrated using a 180 nm silicon-based CMOS technology. We examine how the coupling between these structures and the number of split-rings affects the high frequency impedance of the whole system. The efficient control of impedance is important for designing passive and active terahertz components, such as tunable detectors and sources.

1. Introduction

The coupling of resonating structures has been extensively investigated over the years at a different scale: starting from the conventional electronic circuits with coupled inductors and finishing by coupling atomic states. Despite such scale differences, it is possible to observe many similarities between the interaction of individual atoms and, for instance, plasmonic nanostructures. The well-known effect in atomic physics of the electromagnetically induced transparency was recently demonstrated with optical metamaterials stacked together [1]. Together with the emergence of new effects due to the deeper understanding of the physics of coupled oscillators, there is an important effect of a dramatic increase of their sensitivity to the changes of the electromagnetic properties of the surrounding medium [2]. Therefore, it became feasible to realize a near-field sensor based on coupled resonators for detection and spectral analysis of different 2-D materials, chemical compounds, or biological materials [3] and structures. Furthermore, this concept can be efficiently implemented using the technology platform which is offered by the well-developed mainstream silicon (Si) complementary metal-oxide-semiconductor technology (CMOS). It is commercially available, reliable, and due to the extended metal stack’s functionalities, providing many possibilities for designing high-frequency components. For example, 90-nm Si CMOS technology served as a platform for designing a terahertz (THz) sensor of human body-emitted radiation in a broad range of frequencies 0.1-1.5 THz [4].

In this paper we report on the investigations of electrodynamic properties of a metasurface-coupled THz antenna with the fundamental resonant frequency of 350 GHz which is implemented in a 180-nm CMOS technology.

2. Design of the structure

The structure under investigation is essentially a THz detector based on a pair of n-type CMOS transistors. The detector is equipped with a differential slot antenna with an outer diameter of ≈ 450 µm. A single split-ring resonator has a size of 70 × 30 µm with a gap of 10 µm. The antenna and the split-ring struc-
The graph of the real part of impedance as a function of frequency showing the resonance peaks of (a) a single split-ring structure (the green curve) and a slot antenna (the blue curve), as well as the two resonance peaks of the coupled system of the antenna and the single split-ring (the red curve). (b) The two resonance peaks of the coupled system for one (red curve), three (the black curve), and forty-five (the blue curve) split-ring structures.

3. Results

The numerical simulation of the electromagnetic properties of coupled resonators was performed by the Finite Element Method in CST Studio Suite. The impedance of the slot antenna and the impedance resulting from its coupling with a split-ring is shown in Fig. 2(a). The antenna has resonant peak at 350 GHz and a single split-ring has a resonance nearby, i.e., at 330 GHz. When they are placed together, the electromagnetic coupling results into strong shifting of peak frequencies. We will refer to one peak (270 GHz) as a low-frequency resonance peak and another one (420 GHz) as a high-frequency resonance peak. When the antenna is coupled to three split-rings (as shown in Fig. 1 in blue and azure colors), the peaks shifts even further from each other, i.e., the low-frequency peak to 260 GHz, high-frequency peak shifts to 425 GHz, as shown in Fig. 2(b). If the antenna is coupled to a whole system, face of split-rings (either a matrix of $3 \times 3$ structures or anything larger than that, for instance, a matrix of $5 \times 9$ structures), then the low-frequency peak shifts to 245 GHz and the high-frequency peak shifts to 450 GHz producing 58% splitting from the resonance frequency. Thus, when the coupling occurs between the resonance of the antenna and the continuum of meta-atom states (a surface of split-ring resonators), the low-frequency peak and the high-frequency peak spread further apart than when the coupling occurs between the resonance of the antenna and the single resonance of the split-ring. The coupling becomes stronger when a larger number of resonant structures interact with the antenna and reach their maximum with a matrix $3 \times 3$, since additional structures do not exhibit strong electric fields and weakly contribute to the coupling.

Summarizing this report we show, that the efficient electromagnetic coupling between the slot antenna and the metasurface of split-ring resonators can be realized in a commercially available 180-nm CMOS technology.

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References

Linear-to-circular polarization conversion using time-dependent metamaterials

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Abstract

In this communication we explore a mechanism to achieve an arbitrary conversion of the polarization of electromagnetic waves by using time-dependent metamaterials for real-time polarization rotation and frequency conversion.

1. Introduction

Achieving an arbitrary control of light-matter interaction has been a research topic for decades. In this realm, polarization conversion of electromagnetic (EM) waves (linear, elliptical, circular) can be considered a prominent research area in different fields where polarized EM waves are essential such as antennas and satellite communications [1], near-field focusing [2], [3] and spectroscopy [4], as some examples. In this context, metamaterials and metasurfaces have demonstrated their ability to be utilized in a vast range of applications ranging from lenses, sensors and beam steering devices [5]–[7] up to more complex and intricate scenarios such as solving mathematical equations [8]. Polarization manipulation of EM waves have also been reported using metamaterials [9], [10], demonstrating the importance of such artificial EM media for future technological developments.

Despite the fact that metamaterials and metasurfaces have originally been considered in the time-harmonic (i.e., frequency domain) scenario, they have also been explored in the time domain by changing their EM parameters of permittivity (ε) and/or permeability (μ) in a temporal or spatiotemporal fashion [11]. Controlling wave propagation in space and time was in fact first studied in the last century where it was considered that the values of (ε,μ) were rapidly changed from an initial value (ε₁,μ₁) to (ε₂,μ₂) in a time duration smaller than the period of the incident wave [12]. As it has been shown, in such step-like time-modulated ε(t) and/or μ(t), wavenumber and wavelength are kept unchanged after inducing a temporal change of (ε₂,μ₂) but frequency is changed [13]. This feature has been recently exploited in intriguing applications such as effective medium concepts in the time domain, inverse prism, anti-reflection temporal coatings, temporal aiming, temporal Brewster angle and frequency conversion [14]–[20], to name a few.

Motivated by numerous possibilities that temporal and spatiotemporal metamaterials and metasurfaces can provide, in this communication we theoretically present a technique to achieve arbitrary polarization conversion using time-dependent metamaterials. The physics behind our approach will be presented and discussed in detail demonstrating how linear to circular/linear/elliptical conversion can be achieved in real time.

2. Design and discussion

To begin with, a schematic representation of the proposed technique is shown in Fig. 1. We consider a monochromatic TEM linearly polarized planewave traveling along the y axis in an unbounded medium (see Fig. 1b). The medium is filled with a time-dependent material where its relative permittivity tensor is changed from isotropic (\{(ε₁xx = ε₁zz)\}) to anisotropic \{(ε₃xx ≠ ε₃zz)\} at t = t₁ and then returned to isotropic \{(ε₃xx = ε₃zz = ε₁xx = ε₁zz \}) at t = t₂.

As will be demonstrated theoretically during our presentation at the conference, when changing the relative

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Figure 1: (a) Schematic representation of proposed mechanism for arbitrary polarization conversion using time-dependent metamaterials.
permittivity to an anisotropic value, a set of two forward (FW) and backward (BW) waves are produced at $t_1$ (one related to each $x$ and $z$ components of the electric field, respectively) traveling with a phase velocity that depends on the values of the permittivity tensor before and after inducing the temporal boundary [21]. This feature is then exploited to transform the initial linearly polarized monochromatic plane wave into a plane wave with a circular (or other forms of) polarization. Multiple scenarios will be shown and discussed during the conference such as linear-to-circular, linear-to-linear, linear-to-elliptical as well as frequency conversion using our proposed technique.

3. Conclusions

In this work we explore time-dependent metamaterials for polarization conversion of linearly polarized electromagnetic waves. These results could open new avenues in the design and manipulation of arbitrary polarized fields for applications requiring tailored polarizations and frequency conversion in real time.

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References

Ultra-wideband waveguide embedded graphene-based THz absorber

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Abstract
A novel type of absorber material integrated in a standard metal waveguide is developed for the ultra-wide frequency range of 67-500 GHz. The absorber is based on graphene augmented inorganic nanofibers which are deposited inside a metallic waveguide cassette, allowing them to be utilised in standard waveguide systems. The material’s microstructures result in a low level of reflectance (<15 dB) and good absorbance (> 20 dB) from 110-500 GHz due to the porosity of the sample and attenuation caused by graphene, making them highly suited for wideband terahertz applications.

1. Introduction
Many electromagnetic wave devices such as circulators, couplers, power dividers require to terminate one of the channel, commonly referred to as loads, to eliminate unwanted signals. Millimeter wave terminations are often utilized by back-shorted waveguide sections, which present low reflections and absorb the incident energy due to the presence of an electromagnetic absorbing material inside the waveguide [1]. Such materials usually are shaped in a tapered geometry to improve their reflectivity and operating bandwidth. However, this tapering results in long absorbers of complex geometry.

Here, we present a new kind of ultra-wideband THz absorber which is directly embedded in a standard metallic waveguide, allowing it to be used in conventional THz systems and applications. The absorber material is comprised of graphene-augmented inorganic nanofibers (GAIN) which are deposited in a rectangular waveguide cassette using standard techniques. This cassette is then inserted in a specialised holder to allow it to be integrated in a waveguide system for characterisation.

2. Experimental
Graphene augmented inorganic nanofibers were used as the active absorber material in this work. To realise the GAIN material, a block of gamma-alumina nanofibers with average fiber diameter of 10 nanometers and length of around 2 cantimeters were located in a hot-wall CVD reactor. Carbon coating were deposited from methane at temperature of 1000 Celsius with dwell time of 10 minutes.

The resulting carbon coating represents a few layers of polycrystalline graphene wrapped around alumina nanofibers, where the weight of deposited carbon is 10-13 wt.%.
This fabrication method can be scaled to THz frequencies without any additional complexity.

3. Results and Discussion
The measured S-parameters of a GAIN sample are shown in Fig. 3. A total of 5 repeated measurements were performed at each frequency band. The sample offers return loss greater than 10 dB at frequencies above 100 GHz, with insertion loss (attenuation) as high as 60 dB at 500 GHz, corresponding to an attenuation per unit length of around 20 dB/mm. The highly porous microstructure of GAIN allows electromagnetic waves to permeate into the material, leading to an overall low level of reflectivity. The primary absorption mechanism is likely multiple internal reflections within the sample. Absorbers of this kind can be used for microwave frequencies, and perhaps for millimeter wave frequencies. For higher frequencies (i.e. those in the terahertz (THz) region), the internal dimensions of the waveguides become less than a millimeter. In contrast to existing alternatives, the fabrication method proposed here can be scaled to THz frequencies without any additional fabrication complexity.
4. Conclusions

We presented a new kind of waveguide embedded absorber based on graphene-augmented inorganic nanofibers and demonstrated the electromagnetic properties of this material from 67-500 GHz. In contrast to our previous work, this material is very simple to fabricate and does not require freeze-drying or other chemical treatment. Its reflection coefficient decreases with frequency as a result of the rapid absorption coefficient increase. This material is a very promising absorber for high frequency integrated waveguide systems and applications.

Acknowledgements

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References

Ge$_2$Sb$_2$Te$_5$-based, ultrathin, all-dielectric tunable mid-wavelength infrared perfect absorber

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Abstract

GST-225 (Ge$_2$Sb$_2$Te$_5$) phase change material was recently experimentally reported to exhibit measurable photoconductivity, a well-defined bandgap, and reconfigurable continuous partial crystallization. Sequentially, here we propose an ultrathin, all-dielectric, metamaterial-design based on an asymmetrical optical micro-/nanocavity, enclosing a 10 nm thick GST-225 photoactive layer, inversely optimized for perfect tunable absorption in the mid-wavelength infrared. The perfect absorption, solely in GST-225, can be spectrally-tuned actively (thermally/electrically/optically) by varying the crystallinity, and geometrically using the design parameters, which is highly application beneficial.

1. Introduction

Highly efficient tunable optical absorbers are imperative components in a plethora of applications, e.g. imaging, camouflage, sensing, spectroscopy, etc. Devising optimal ultrathin absorbers requires efficient coupling and confinement, for which the most mature approach, based on Fabry–Pérot cavity, is the bandwidth restricted, resonant cavity-enhanced (RCE) photoabsorption. Accelerated by the extensive development of micro/nanofabrication capabilities, modern approaches employ evolving plasmonics, metasurfaces (MS), and metamaterials (MM) concepts that can support thinner than RCEs photo-active layers with significantly thinner overall structures [1].

Chalcogenide phase-change materials (PCMs) are industrially mature materials that can be switched between two stable solid states, amorphous and crystalline. The reversible PCM switching is performed using optically, electrically, or thermally induced heating. Commercially, PCMs are the building blocks of nonvolatile optical (DVDs/Blu-ray) and electronic (PCRAM) data storage devices. In recent years, PCMs have been utilized in various photonic devices, as tunable metalenses, photonic memories, meta devices [2], metasurface spectral filters [3], and others. In the mid-wavelength infrared (MWIR), Chalcogenide Ge$_2$Sb$_2$Te$_5$– GST-225 extinction coefficient is significantly lower than at the visible (VIS) and near-infrared (NIR) spectrum. Thus, previous studies that offered GST in MWIR absorptive devices, such as sensors and pixel arrays [4], focused mainly on absorption in metals due to surface plasmon (SP) effects. Whereas the GST served as a spacer or surrounding media to spectrally shift the SP resonance. Such absorbers reported so far, can serve as thermal-signature, in particular bolometric, photodetectors [4].

Recently, measurable photoconductivity [5] of GST-225 (Ge$_2$Sb$_2$Te$_5$) with a well-defined bandgap [6], was experimentally verified at the VIS and NIR. Additionally, reconfigurable continuous partial crystallization of GST, stable across several phase change cycles, was demonstrated [3]. Following these reports, here, we propose an ultrathin, all-dielectric MM design with 33 nm effectively thick GST photoactive layer, inversely optimized to exhibit perfect tunable absorption in the MWIR.

2. Design materials, methods, and results

The absorber material is GST-225 with the wavelength-dependent complex RIs at partial crystallinities $n_{\text{eff}}(\lambda)$ calculated according to Equation (1) below.

$$\varepsilon_{\text{eff}}(\lambda) = \frac{m \times \varepsilon_{c}(\lambda) - 1}{m \times \varepsilon_{c}(\lambda) + 2} + (1 - m) \times \frac{\varepsilon_{a}(\lambda) - 1}{\varepsilon_{a}(\lambda) + 2}$$

where $\varepsilon_{\text{eff}}, \varepsilon_{c}, \varepsilon_{a}(\lambda)$ is the permittivity of partially crystallized, crystalline, and amorphous-GST, respectively. $m$ is the crystallization fraction spanning from 0 to 1. Following [2] and industrial maturity, to avoid oxidation of GST and interatomic diffusion to other materials, ZnS:SiO$_2$ was selected to enclose each GST interface. To support the absorption enhancement mechanisms discussed below, MWIR transparent Ge and CaF$_2$ are chosen for high RI contrast grating and low RI substrate, respectively, see RIs in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>$n + ik$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaF$_2$</td>
<td>1.4</td>
</tr>
<tr>
<td>ZnS:SiO$_2$</td>
<td>1.6</td>
</tr>
<tr>
<td>Ge</td>
<td>4.03</td>
</tr>
</tbody>
</table>

Due to considerable $\Delta n_{\text{GST}} \approx 1.7 + i 0.18$ variations, the design’s coupling and confinement properties should be tolerant enough to maintain and tune the high absorption. For this aim, we exploit a strong electromagnetic (EM) confinement mechanism, associated with photonic bound states in the continuum (BICs) that is based on localization of Bloch surface-localized eigenstates in photonic crystals. Such BICs arise due to interference between various leakage channels excited from free space. We employ this mechanism by establishing a generalized design schematic illustrated in Fig. 1a, in which $s$-dual, Ge-Air (G$_1$) GST-ZnS:SiO$_2$ (G$_2$), grating asymmetrical cavity encloses a 10 nm GST absorber. The smooth ZnS:SiO$_2$ enclosures are design constraints for protective layers.
To maximize the tunability range we optimize the design parameters for $m = 0.4$. The common period $\Lambda$, grating thicknesses $h_1$ and $h_4$, grooves widths $W_1$ and $W_4$, the shift between the grooves $s_{4-1}$, and the ZnS:SiO$_2$ spacers thicknesses $h_2$ and $h_5$, are all optimized to maximize the peak normal incidence s-polarization absorptance $A_{\text{max}}^{(s)}$ at $\lambda_0 = 3.5 \mu m$. The optimization is adjusted to favor minimum overall thickness, specifically, the photoactive region that includes the GST grooves of $G_4$ and the adjacent GST (fixed to 10 nm in the optimization) film. The optimization process yielding the inversely designed parameters' values is applied with an in-house simulation and optimization tool specified in [1]. The optimized values are manually rounded and refined for fabrication convenience, which slightly adjusts $\lambda_0$ to $3.44 \mu m$. The final values of the design parameters are specified in Table 2, and the resulting tunable $A^{(s)}(\lambda)$, for 0 to 1 sweep of $m$, is shown in Fig. 1b.

Table 2: The dimensions, in microns, and performance of the optimized MM design.

<table>
<thead>
<tr>
<th>$h_1$, $h_2$, $h_3$, $h_4$, $h_5$, $\Lambda$, $W_1$, $W_4$, $s_{4-1}$</th>
<th>$m$</th>
<th>$\lambda_{\text{peak}}$</th>
<th>$A_{\text{max}}^{(s)}$</th>
<th>$\delta_p (\lambda_{\text{peak}})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.09, 0.1, 0.01, 0.04, 0.017, 2, 1, 0.87, 0.235</td>
<td>0.4</td>
<td>3.440</td>
<td>0.995</td>
<td>7.08</td>
</tr>
<tr>
<td>0.1</td>
<td>3.364</td>
<td>0.646</td>
<td>34.62</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3.704</td>
<td>0.813</td>
<td>1.65</td>
<td></td>
</tr>
</tbody>
</table>

3. Discussion and Conclusions

The total design thickness, excluding the substrate, is $t = 257 \text{ nm} < \frac{2\lambda}{\Lambda}$, and the effective thickness of the photoactive region $t_{\text{eff}} = 32.6 \text{ nm}$ is three orders of magnitude thinner than the GST penetration depth at $\lambda_{\text{peak}} = 3.364 \mu m$ for $m = 0.1$ ($t_{\text{eff}} < 10^{-3} \times \delta_p (\lambda_{\text{peak}})_{m=0.1}$). Considering these ultrathin dimensions of the design, it is quite remarkable that $A_{\text{max}}^{(s)}|_{m=0.4} > 99.5\%$, $A_{\text{max}}^{(s)}|_{m=0.2} > 0.81$, and $A_{\text{max}}^{(s)}|_{m=0.1} > 0.64$, which is a result of the strong EM confinement and efficient coupling. In addition to the active $m$ absorptance tuning, we visualise in Fig. 1c an effective geometrical tuning of the high absorptance due to variations in $\Lambda$. We preform similar examination for relative variations in the gratings' shift $\Delta s_{4-1}$, which demonstrated that the design is fairly tolerant to misalignment fabrication errors, not shown.

Due to the discussed properties of the proposed all-dielectric design, including on/off and spectral tunability of the perfect absorptance, ultrathin thickness, fabrication tolerances, and technological mature materials and architecture, it is fair to conclude that it can benefit a host of applications, such as IR multi-/hyper-spectral sensing, spectroscopy, and imaging, thermal signature manipulations, free-space optical communication, etc. Such ultrathin all-dielectric designs suggest a decent alternative to the variety of enhanced IR, SPs and metal MSs based, devices.

References


Metamaterials and negative index materials
THz Metamaterial Device Design with SRRs

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Abstract

THz device design method for periodic structures using single and double gap split ring resonators (SRRs) is introduced. The method involves implementation of split ring resonators with application of network parameters. The closed form relations are developed and verified with electromagnetic and circuit simulators. The prototype then has been built and measured. The results are compared, and agreement has been observed between analytical, simulation and measurement results. The proposed method can be implemented to design devices such as sensors, antennas, impedance matching networks and resonators at the THz range.

Keywords— THz, sensing, radiation, metamaterial, SRR, absorption.

1. Introduction

Metamaterials have been investigated by several researchers due to their design advantages. These advantages include by being able to artificially control the electric and magnetic properties of the material independent of its existent material properties. This motivated implementation of metamaterial devices at THz ranges [1-3].

The concept of negative index was first introduced in 1968 [4]. The experimentation showing the possibility of having material characteristics with negative permittivity and permeability was demonstrated by Smith [5]. The negative refractive index parameters are obtained using split ring resonators (SSRs) with thin wire posts. SSRs contribute to the negative permeability whereas CPW thin wire posts contribute to the negative permittivity [5]. This configuration is then revised to obtain metamaterial transmission lines by implementing SSRs and coplanar wave (CPW) transmission lines.

In this paper, the complete formulation of THz metamaterial device for periodic structures using single and double single gaps is given. Practical equivalent circuit model is proposed and used with network parameters to obtain the formulation of the periodic structure. The proposed method is then verified via electromagnetic and circuit simulators. The prototype has been built and measured. It has been confirmed that the analytical, simulation and measurement results are all in agreement. The proposed method can be used to design THz metamaterial devices for applications such as sensing, radiation, polarization and absorption.

2. Formulation, analysis and results

2.1. Single Gap SRR

The single gap SSR that can be implemented as part of THz unit cell is shown in Fig. 1. Every split ring resonator can be considered as LC resonator circuit. The equivalent circuit proposed for the single gap SRR is shown in Fig 1b. Ring itself has a self-inductance $L_T$. Total capacitance is a parallel combination of the gap capacitance, $C_g$ and the inner space capacitance of the ring, $C_s$. Self-inductance can be calculated from the closed ring formulation given in [6, 7] excluding the gap.

$$L_T = 0.002 \left( \ln \frac{4l}{c} - \gamma \right) \mu H$$

In (1), $\gamma$ is constant and equal to $\gamma = 2.451$. The total equivalent capacitance can be expressed as

$$C_{eq} = C_g + C_o = \frac{\varepsilon_0}{g} \left( \pi (r_{ext} - \frac{2c}{2'2}) - \frac{2}{2'} \right) C_{pol}$$

where

$$C_{pol} = \frac{\varepsilon_0}{c \varepsilon_0}$$

The analytical results are compared with 3D electromagnetic simulation results and illustrated in Fig. 2. The close agreement between simulation and analytical results are verified as shown in the figure 2.

2.2. Double Gap SRRs

The double gap SSR and its proposed equivalent circuit model to be implemented at THz range is developed and shown in Fig. 3. $L_1$ and $L_2$ are equal and can be calculated using equation (1) with a length equal to

$$l = \pi r_{ext} - g$$

The total inductance is then found from

$$L_T = L_1 + L_2$$

$C_{g1}$ and $C_{g2}$ are also equal and can be calculated from

$$C_g = \frac{\varepsilon_0}{g}$$

Figure 1: (a) Single gap SSR and (b) The equivalent circuit proposed for a single gap SSR.
The total gap capacitance is then obtained as
\[ C_{gr} = \frac{C_{g1} \times C_{g2}}{C_{g1} + C_{g2}} \]  
(7)

Total capacitance of the structure is given by
\[ C_{eq} = C_{gr} + C_o = \frac{C_{g1} \times C_{g2}}{C_{g1} + C_{g2}} + \left(\pi \left(r_{ext} - \frac{g}{2}\right) - \frac{g}{2}\right) \times C_{pol} \]  
(8)

2.3. Measurement results
For EM simulation Floquet port is used. Floquet port is designed exclusively for planar-periodic structures to simulate the boundary condition of a unit cell of an infinite structure. This port is based on Floquet’s theorem which expresses the field in a periodic structure in terms of field of unit cell with a propagation factor \[ [8] \]. For practical representation of floquet ports we used a rectangular waveguide and unit cell is kept in the middle. Results are aligned with the simulation to a great extent. Reason behind small deviation is use of other insulated materials to keep the unit cell in the middle. The measured result for \( S_{11} \) is illustrated in Figure 4.

3. Conclusions
In this paper, the complete modeling and formulation of single and double gap SSRs have been presented. The proposed analytical models are then verified with 3D electromagnetic simulators. It has been confirmed that there was agreement between simulation, analytical and measurement results. The proposed method can be used as part of a unit cell to develop a periodic structure which can then be used for applications including sensing, radiation, absorption, and polarization.

References
Chemically Modulated Hyperbolic Metamaterials

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Abstract

Hyperbolic Metamaterials (HMMs) are multilayered optical nanomaterials that exhibit, due to their intrinsic anisotropy, optical topological transitions (OTTs). Here, we propose and experimentally demonstrate an all zirconium-based hyperbolic metamaterial. We have selected ZrN/ZrO2 as specific example, as these earth-abundant refractory materials offer unique mechanical and thermal stability in extreme environments, such as high temperatures above 2000°C. Alternating the reactive gases, oxygen and nitrogen during reactive sputtering, enables continuous growth of a chemically modulated nanomaterial. Using experiments and simulations we show that this chemically modulated metamaterial exhibits optical topological transitions in the visible and infrared range. Since the OTTs expand to the near infrared, our results have the potential to facilitate the development of thermal emitters for thermophotovoltaic (TPV) energy applications.

1. Introduction

Material scientists have historically used the rule of mixtures to homogenize the material properties such as elasticity and conductivity in composite materials. This simple rule is readily applied to materials with anisotropic electromagnetic properties, borrowing the equations for summing resistances in series and in parallel. In the case of extreme anisotropy in layered optical materials, the effective permittivity along the directions parallel and perpendicular to the surface can flip sign giving rise to a topological transition in the isofrequency surface from a closed to an open geometry, typically a hyperboloid [1]. The dispersion relation of electromagnetic waves in such a metamaterial reads,

\[ \frac{\omega^2}{c^2} = \frac{k_z^2}{\varepsilon_{\parallel}} + \frac{k_x^2 + k_y^2}{\varepsilon_{\perp}}. \] (1)

Two different kinds of hyperbolic metamaterials (HMMs) exist: type I (\(\varepsilon_{\perp} < 0, \varepsilon_{\parallel} > 0\)) and type II (\(\varepsilon_{\perp} > 0, \varepsilon_{\parallel} < 0\)). These two optical phases exhibit very different optical properties, which have been exploited in applications ranging from subwavelength imaging to thermal emission control for energy applications [2][3]. The most studied HMMs are obtained by combining layers of two different materials fabricated using physical vapor deposition techniques. Common materials combinations with hyperbolic behavior in the visible range include metal-dielectrics and metal-semiconductor systems [2]. The most used metals for plasmonic applications, silver and gold, are scarce and costly [4], and have relatively low melting temperatures, limiting their application in energy research [5]. The deposition of semiconductors and dielectrics, on the other hand, is limited to slow vapor deposition techniques such as e-beam evaporation and radio frequency (RF) sputtering [6]. Trying to overcome this limitations, we propose and fabricate a refractory chemically modulated hyperbolic metamaterial (CMHMM) based on earth-abundant Zr [4], which shows both type I and type II hyperbolicity within the visible range.

2. Results

Using a Zr target and a commercial magnetron sputtering system thin film ZrN/ZrO2 multilayer systems have been deposited by solely controlling the flux of nitrogen and oxygen gas into the chamber. The use of a single target and the deposition rates in the order of tens of nanometers per minute renders the fabrication process both fast and scalable. Moreover, both ZrN and ZrO2 have melting temperatures up to three times higher than those of conventionally used plasmonic metals. Figure 1 a exemplifies the proposed geometry and its periodicity. The crystal structure and texture of the HMM was determined by X-Ray Diffraction, and the film thickness was obtained by milling and imaging cross sections using a Focussed Ion Beam Scanning Electron Microscopy, as shown in 1 b. The permittivity of each HMM component was determined using ellipsometry. In a second step the anisotropic permittivity components were calculated using effective medium theory (EMT), given by

\[ \varepsilon_{\parallel} = \frac{\varepsilon_m d_m + \varepsilon_d d_d}{d_m + d_d}, \quad \varepsilon_{\perp} = \frac{d_m + d_d}{d_m + d_d}. \] (2)

Here, \(d_i\) is the thickness of each layer and \(\varepsilon_i\) its corresponding permittivity. The subscript \(m\) indicates the metallic component and \(d\) the dielectric component, in our case ZrN and ZrO2, respectively. The fraction of metal is thus given by \(d_m/(d_m + d_d)\).

Figure 1 c shows \(\varepsilon_{\parallel}\) and \(\varepsilon_{\perp}\) for different ZrN filling frac-
Figure 1: (a) Model of the expected configuration of a 6 layers system. (b) Cross-section view of an as-produced multilayer system. The colour on ZrN has been superposed for illustrative reasons. (c) Real parts of $\varepsilon_{\perp}$ and $\varepsilon_{||}$ of systems with different metallic fraction for wavelengths ranging from 400 nm to 1500 nm (violet and red, respectively). The color scheme in the background represents the losses (summed imaginary parts of $\varepsilon_{\perp}$ and $\varepsilon_{||}$). (d) Optical phase diagram depicting the different zones: effective dielectric ($\varepsilon_{\perp} \cdot \varepsilon_{||} > 0$), effective metal ($\varepsilon_{\perp} \cdot \varepsilon_{||} < 0$), Type I HMM ($\varepsilon_{\perp} < 0$, $\varepsilon_{||} > 0$), and Type II HMM ($\varepsilon_{\perp} > 0$, $\varepsilon_{||} < 0$).

...tions and the expected loses, given by the imaginary components of those permittivities. Figure 1 d depicts at what wavelengths each optical regime can be found depending on the metallic fraction. We analyse the light-matter interaction in the different optical phases of the HMM by resorting to full-wave finite element simulations (Comsol Multiphysics 5.5) and the transfer matrix method. Specifically, we discuss the role of high-k propagating modes within the two HMM phases and the ENZ (Epsilon Near Zero) point. This two approaches allow us to overcome limitations of EMT with respect to design parameters such as the unit cell size, the number of layers or the influence of roughness. To validate the optical topological transitions in the experiment, the calculated reflectivities of different polarizations are afterwards compared with the experimental results.

3. Outlook

Our refractory HMM presents OTTs in the near IR region, where thermal emission of bodies at temperatures above 1000°C mostly occurs. When heated to those temperatures, our designed structure would selectively suppress the thermal emission of long wavelength photons while providing high emissivity at energies above the OTT. This has been previously proved to enhance the efficiency of low-bandgap photovoltaic materials [3]. Hence, our findings pave the way to explore the use of the metamaterial as a selective thermal emitter for TPV applications.

Acknowledgement

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References


Tunability of Epsilon-Near-Zero behavior in a Self-assembled Liquid Crystal – Nanoparticle Hybrid Metamaterial

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Abstract

We report experimental evidence of tunable epsilon-near-zero (ENZ) behavior in a self-assembled lamellar superstructure consisting of Au nanoparticles capped with a photo-active chiral liquid crystal ligand. Upon irradiation with UV, the LSPR peak of Au red-shifts by ~10 nm which restores with white light. The effective permittivity indicates ENZ behavior in the visible spectrum with a bandwidth of ~45 nm which gets enhanced by a factor of 1.6 on UV illumination. Theoretical calculations based on effective medium approach, support the experimental findings.

1. Introduction

Metamaterials are emerging materials where light-matter interactions are manipulated by tailoring the effective medium parameters like permittivity (ε) and permeability (μ).¹ Materials exhibiting ‘ε’ approaching zero at frequencies (ω) close to bulk plasmon frequency (ωp) are known as ENZ materials.² At the ENZ wavelength, interesting phenomena such as diverging phase velocity, the consequent wavelength expansion (λENZ = λ0 / neff, where λ0 is the free space wavelength, neff is the effective refractive index of the system), and a spatially uniform phase occur inside the material. ENZ behavior has been observed over a broad spectral regime, including microwave, infrared, visible, and ultraviolet, in a variety of materials³ such as metals, semimetals, doped semiconductors, and photonic crystals. Self-assembly of nanoparticles into a periodic arrangement is a facile technique to realize metamaterial-based devices on a large scale. Lewandowski et al⁴ have shown thermally tunable ENZ behavior in the optical regime in a self-assembled system of Ag nanoparticles capped with a liquid crystal (LC) ligand. However, thermal tunability still requires the sample to be cycled to high temperatures, which may be detrimental to the desired properties. In the current work, we demonstrate the possibility to dynamically modify the metamaterial properties using an optical field applied to a photo-responsive sample at ambient temperatures. The system wherein Au nanoparticles (NPs) are capped with a photo-active LC ligand, forms a NP-LC hybrid structure. The self-assembly and the plasmonic behavior of the liquid crystal nanoparticle system are extensively studied. The system forms a soft metamaterial with a layered superstructure exhibiting ENZ behavior in the optical regime at room temperature. Further, the ENZ bandwidth is tuned efficiently by irradiating the material with actinic light.

![Figure 1: Au NP capped with photoactive LC ligand self assembles into periodic lamellar structure as can be seen in HRTEM image.](image-url)

2. Results and Discussion

2.1. Optical tuning of plasmon resonance:

The UV-Visible absorption spectra for the thin film of the sample deposited on quartz plate is shown in Figure 2. The two peaks at 380 and 450 nm correspond to π - π* and n - π* transitions of the azobenzene (photoactive) group present in the LC ligand. In addition to the azobenzene peaks, a third strong peak is seen at 580 nm, which corresponds to the localized surface plasmon resonance (LSPR) peak of gold.

![Figure 2: UV-Vis absorbance spectra in the (a) pristine state and (b) pristine, UV-irradiated and white light illuminated states for the thin film of GNP-ALC. Inset to (b) shows the normalised profiles of the Au peak in the three states.](image-url)
When the thin film of GNP-ALC is irradiated with UV (2.5 mW for 15 min), the LSPR peak of Au at 580 nm gets red-shifted to 593 nm, as shown in the inset to Figure 2. The photo-isomerization from ‘trans’ to ‘cis’ state leads to an increase in the dipole moment of the azobenzene moieties, and hence the dielectric permittivity of the ALC ligand. Additionally, due to the bent-shape of cis isomers, the interlayer spacing, and also the interparticle distance between the Au NPs decreases. The above factors contribute to the red-shifting of LSPR peak with UV irradiation.

Upon white light irradiation (for ~15 minutes), the LSPR peak reverts to its original position (~582 nm) (see Figure 2), again, due to the reverse photo-isomerization. Thus, an optical field-induced tuning of the LSPR peak wavelength by ~ 10 nm is obtained in the visible regime.

2.2. Epsilon-near-zero behavior:

The amplitude (psi) and phase (delta) of the reflected light acquired for various incidence angles from the ellipsometry are fitted to a model to extract the effective optical parameters, $\varepsilon_{\text{eff}}$ and $n_{\text{eff}}$. The model to fit the ellipsometry data is developed based on effective medium approach with Bruggeman analysis, where the system is approximated as a mixture of organic moieties (whose properties are reflected by harmonic oscillator) and Au (whose properties are reflected by the built-in permittivity function of Au).

![Figure 3: The real and imaginary parts of the effective permittivity ($\varepsilon_{\text{eff}}$) extracted from the psi and delta values obtained from ellipsometry in the (a) pristine and (b) UV irradiated states](image)

The real and imaginary parts of effective permittivity ($\varepsilon_{\text{eff}}$) extracted from the fit are given in Figure 3. The $\varepsilon_{\text{eff}}$ exhibits a harmonic oscillator-like behavior with the real part of permittivity, Re($\varepsilon_{\text{eff}}$), featuring a dip followed by a peak, while the imaginary part, Im($\varepsilon_{\text{eff}}$) showing a peak in the same regime. In the pristine state, the Re($\varepsilon_{\text{eff}}$) crosses zero (goes from +ve to -ve) at 522 nm. The ENZ regime extends up to 565 nm with an approximate bandwidth of 43 nm, as seen from Figure 3a. For the UV irradiated case, $\varepsilon_{\text{eff}}$ extracted using the same model exhibit the following features: The Re($\varepsilon_{\text{eff}}$) crosses zero at 508 nm itself, with the ENZ behavior extending to 576 nm. Hence the effective ENZ bandwidth is increased to 68 nm, as shown in Figure 3b. Thus, UV irradiation enhances the ENZ range by a factor of ~ 1.6 compared to that of the pristine case. Theoretical simulations carried out using the Claussius-Mossotti effective medium approach support the experimental findings.

Thus, GNP-LC system, with a chiral lamellar superstructure leading to periodic self-assembly of Au nanoparticles, exhibits a tunable LSPR, and ENZ behavior in the optical regime. The LSPR tunability brought about by the photo-induced effect augments the ENZ bandwidth at room temperature.

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Metamaterial-assisted Inductive Power Transfer using Transmission-Line Mode

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Abstract

In this paper, a metamaterial-assisted inductive power transfer (IPT) system, based on the transmission-line (TL) mode of unit cells, is presented for the first time. The proposed metamaterial (MTM) topology is shown to have a similar gain effect on the efficiency of the system as conventional μ-negative (MNG) MTMs, if employed in the magnetic-reflector configuration instead of the magnetic-lens one. The obtained numerical results also indicated that TL-mode cells have μ-positive (MPS) paramagnetic response and are inherently dual band.

1. Introduction

In the last two decades, there has been an increasing demand for efficient inductive power transfer (IPT) systems. However, due to the evanescent nature of the near-field modes involved in magnetic coupling, their efficiency over distance is generally small. Many different strategies have been suggested in literature aiming to improve IPT efficiency, some of which are used to compensate the decay of the magnetic coupling between IPT drivers.

As discussed in [3], metamaterial-enhanced coupling (MEC) is basically an extension of RMC, with both topologies exploiting the equivalent μ-negative (MNG) response of split-ring (SRRs) or spiral resonators (SRs) to create a sort of focalization of the near field. Nonetheless, MEC tends to outperform RMC, because it takes advantage on both the high-Q of the unit cells as well as their interaction in the lattice, reinforcing the amplification-like behavior around the operating frequency.

In this work, a novel MTM-assisted IPT systems based on the transmission-line (TL) mode of bifilar-coil unit cells is presented for the first time. The obtained numerical results indicate that TL-mode based MTMs present a non-negligible PTE gain response when employed in the magnetic-reflector configuration, this is, positioned behind the IPT drivers, instead of between them, as in the case of magnetic-lens. Unlike MNG MTM-based lenses, TL-mode MTM-based reflectors present μ-positive (MPS) and are inherently dual band.

2. TL-mode of Bifilar Coils

As shown in Figure 1, any bifilar coil structure can be excited in TL or antenna mode. When the coil is excited using the TL mode, its radiation resistance is set to a minimum but almost no magnetic flux can pass through it. Therefore, TL-mode coils can be used as efficiently as high quality factor cells for MTM-based magnetic reflectors, as it is further demonstrated in this section. One important feature of TL-mode coils is that their response cannot be controlled by lumped capacitors connected in series with the conductor, like in MNG MTM lenses, because in this case the intrinsic capacitance of the TL-mode coil will also be in series with the added capacitance:

\[
\frac{1}{C_{\text{total}}} = \frac{1}{C_{\text{added}}} + \frac{1}{C_{\text{intrinsic}}} \tag{1}
\]

which means \(C_{\text{total}} \rightarrow C_{\text{intrinsic}}\), since \(C_{\text{added}} \gg C_{\text{intrinsic}}\). Hence, the tuning control of the TL-mode unit cell must be made by connecting the lumped element in parallel with the coil conductor, as shown in Figure 2.

Figure 1: Currents on TL (a) and antenna (b) mode bifilar coils.
3. Results and Discussion

3.1. TL-mode Unit Cell as a Magnetic-Reflector

For the numerical simulations presented in this section it was considered a TL-mode unit cell, composed by copper conductors using air as substrate, with the following characteristics:

- \( d_{\text{tm}1} = 48 \text{ mm} \)
- \( C_{\text{SMD}} = 10 \text{ pF} \) up to \( 1 \text{ nF} \)
- \( w = 1 \text{ mm} \)
- \( g = 1 \text{ mm} \)

When the proposed TL-mode cell is employed as a magnetic reflector, placed not in between but behind the TX and RX coils, as shown in Figure 3, a high MTM gain is also achieved around the operating frequency at \( f_0 = 186 \text{ MHz} \), as shown in Figure 4. The simulations were performed considering excitation coils outer dimensions \( L_{\text{out}} = 60 \text{ mm} \), separated by \( D = 25 \text{ mm} \) from each other, and separated by \( D_2 = 3 \text{ mm} \) from their assistant reflector. In fact, the obtained gain with this strategy is even higher (about 15 dB) than the one typically obtained with MTM lenses (about 10 dB).

By measuring the S-parameters of TL-mode unit cell, the equivalent relative permeability \( \mu_r \) can be determined [4]. The results highlighted in Figure 5 show that \( \mu_r \) response presents a loss-free \((\text{Im}(\mu_r) \approx 0)\), paramagnetic response \((\text{Re}(\mu_r) > 1)\) in its gain region, and not a MNG one, as MTM lenses. In fact, paramagnetic materials are already employed as reflectors in UWPT systems in order to increase their performance, as the one presented by Do Won Kim, during the 2019 Autonomous Underwater Technology (AUT) Conference [5]. However, the reflectors proposed by [5] are typically made of an array of bulky ferromagnetic bars, as shown in Figure 6. Consequently, TL-mode based MTMs could be an effective replacement with the advantage of being planar (easy to integrate), low-cost (made of ordinary materials) and power efficient.

Moreover, TL-mode cells present a feature which is particularly interesting for simultaneous power and data transmission: they are intrinsically dual band, presenting two gain regions, as it is shown in Figure 7. Nonetheless, as it can be seen in Figures 7(a) and 7(b), the proposed tuning strategy for TL-mode cells can only control the gain region at the lower band. In this way, when \( C_{\text{added}} = 10 \text{ pF} \) is changed to \( C_{\text{added}} = 1 \text{ nF} \), only the first gain band moves to a lower operating frequency, while the second gain band remains completely transparent to the tuning element. Moreover, the second resonance of the TL-mode cell tends to present a much lower gain than the first one.
3.2. Magnetic Flux Reflection Mechanism of TL-mode based MTM Slabs

As shown in Figure 8, a 3x3 lattice made of TL-mode unit cells, with $C_{\text{added}} = 10 \text{ pF}$, was evaluated in order to investigate how the magnetic flux is reflected by a TL-mode based MTM. The simulated $S_{21}$ response of the TX and RX coils assisted by the proposed 3x3 MTM slab is highlighted in Figure 9, while Figure 10 shows the H-field at the MTM operating frequency 196 MHz. As it can be seen in Figure 10, the vortex-like behavior of the H-field on the surfaces of the MTM slabs causes the magnetic flux to be reflected. Notice that gain resonance of the 3x3 MTM, at $f_0 = 196 \text{ MHz}$, is slightly different of a sole unit cell, at $f_0 = 186 \text{ MHz}$, due to the mutual coupling of the lattice cells.

4. Conclusion

In this work, it was shown that TL-mode coils can be effectively used as unit cells of artificial magnetic reflectors. The response of the proposed TL-mode cell can be controlled by a parallel tuning capacitor. They are naturally dual band, but its second operating band presents low gain and cannot be controlled by the proposed tuning mechanism. Finally, further studies should investigate mechanisms for equalizing the TL-mode cell gain in both bands and how to control them.

References


Metasurfaces and flat optics
All-dielectric metasurface doublet enabling beam steering and polarizing beam splitting

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Abstract
Multifunctional metasurfaces, fulfilling a variety of tasks, have attracted drastically growing interest. Here we proposed and embodied an all-dielectric metasurface doublet (MD) by vertically concatenating twosome arrays of rectangular nanoresonators on either side of a quartz substrate, in which distinct phase profiles are encoded for orthogonally polarized light. Bifunctional beam manipulation including enlarged steering and polarizing beam splitting was enabled by the MD. The superior performance of the proposed device paves the way to large-scale photonic integrated applications.

1. Introduction
Optical elements such as Risley prisms, lenses, spherical mirrors and polarizing beam splitters are ubiquitously applied in constructing sophisticated systems like light detection and ranging, afocal telescopes, and quantum computing. The combination of several free-space optical components imposes strict requirements upon their alignment, making the system bulky. To surmount this hurdle, optical metasurfaces consisting of subwavelength meta-atoms, which can flexibly manipulate the incident wavefront, have demonstrated performance comparable or superior to the conventional refractive/diffractive elements [1,2]. In this work, we proposed and experimentally realized an all-dielectric metasurface doublet (MD) that enables bifunctional beam manipulation in the near-infrared (NIR) regime, encompassing enlarged beam steering and polarizing beam splitting. For the MD, the optical transfer characteristics can be polarization-tailored in terms of the phase and amplitude to engineer the phase profiles, which are distinct for the transverse-electric (TE) and transverse-magnetic (TM) polarization. The suggested approach paves the way to ease the optical systems with the help of all-dielectric multifunctional metasurfaces.

2. Results and Discussions
Figure 1 shows a schematic of the proposed NIR bifunctional MD. The phase and amplitude responses of the nanostructures are polarization-controlled, resulting in implicit phase profiles of the MD, which are distinct for the incident light with the electric field aligned parallel to the x-axis (TE polarization) or y-axis (TM polarization). An incident TM-polarized beam deflects to assume an enlarged angle of propagation, equivalent to \( m \) times the angle of incidence (\( \theta_{inc} \)). Simultaneously, a TE-polarized beam goes straight through the MD, thereby facilitating the splitting of an orthogonally polarized beam. Dual-layer of high-contrast gratings, serving as bi-metasurfaces (MS1 and MS2) constructed by a group of hydrogenated amorphous silicon (a-Si:H) rectangular dielectric resonators (RDRs), are deposited on a quartz substrate with a desired thickness of \( t = 902 \) μm. The geometrical parameters are fixed at \( L_1 = 400 \) μm and \( L_2 = 250 \) μm, respectively. Note that the width (w) of the RDRs is along the y-direction, while the length of each RDR is the same as \( L_2 \). The inset of Fig. 1 illustrates the cross-section in the yz-plane of the RDR. The device is designed at the working wavelength of \( \lambda = 1550 \) nm. All the selected RDRs have the same height at \( h = 930 \) nm and are

Figure 1: Schematic illustration of the proposed bifunctional MD.
incorporated together to exhibit a period of $p = 800$ nm along the y-axis. Rigorous simulations were executed to validate the device performance using a finite difference time domain method software, FDTD Solutions (Lumerical, Canada).

We practically investigated the enlarged beam deflection of the proposed MD by utilizing the experiment set-up as shown in Fig. 2(a). The steering angle ($\theta_{\text{in}}$) pertaining to the MD is measured when $\theta_{\text{in}}$ is scanned from 0 to 12°, which is fulfilled by manually rotating it. The angle of deflection of the light is obtained as $\theta_{\text{out}} = \theta_{\text{in}} + \theta_{\text{def}}$. The transfer characteristics of the proposed MD for the escalated deflection angle are depicted in Fig. 2(c). The slopes of the fitting lines corresponding to the measured and calculated results are 3.55 and 3.25, respectively. Both the mean values and the error bars in relation to the standard deviation were obtained from multiple measurements. The beam profiler was simultaneously displaced to capture the beam while altering $\theta_{\text{in}}$. A collection of beam profiles as displayed in Fig. 2(b) were separately captured at a position where the beam profiler is 35.6 mm from the MD.

The proposed MD is anticipated to act as a planar polarizing beam splitter, mimicking a Rochon prism. The ordinary ray component remains on the same optical axis as the input, while the extraordinary ray component deviates from it by an angle hinging on $\theta_{\text{in}}$. A plane wave is impinging upon the MD at an angle of 2°, carrying both TE and TM polarizations. The calculated far-field intensity, proportional to $|E_y|^2$, has been individually normalized and plotted in Figs. 3(a) and 3(b). Insets in the figures reveal the observed far-field profiles for the TE and TM cases. Overall, for the transmitted TE and deflected TM beams, there is a decent correlation between the measurement and calculation outcomes. However, the imperfect beam splitting might be incurred by fabrication errors, such as surface/edge roughness of the RDR and disparities in the realized structural dimensions [3]. The proposed all-dielectric MD is designed to play an integral role in the near-infrared region (NIR). Three wavelengths (1500, 1550, and 1600 nm) were considered to verify the MD performance in the numerical simulations. The light intensities, proportional to $|E_y|^2$, are shown in Fig. 3(c). The beam deflection facilitated by the MD for each wavelength has been accordingly authenticated. The cross-section extracted from the captured beam profiles are fitted with a Gaussian distribution, as plotted in Fig. 3(d). The deflected beam for the MD provided a slight angular shift while preserving nearly the same full width at half maximum for the three wavelengths, indicating a wide working wavelength range.

![Figure 2](image1.png)  
**Figure 2:** (a) Test set-up for characterizing the performance of proposed MD. (b) Captured beam profiles while rotating the MD. (c) Observed beam deflection characteristics.

![Figure 3](image2.png)  
**Figure 3:** Calculated intensity distribution for the proposed MD for (a) TE- and (b) TM-polarized light. Inset: captured beam profiles. (c) Calculated and (d) measured intensity distributions for the MD. The wavelength was varying from 1500 to 1600 nm for $\theta_{\text{in}} = 2°$.

### 3. Conclusion

An all-dielectric MD enabling beam steering and polarizing beam splitting was realized. Its versatility was realized by engineering the phase profiles for the MD, which could be triggered by the incident light polarization. In view of the achieved performance in the NIR, it was categorically judged the proposed metasurface device will play a pivotal role in large-scale integrated photonics applications.

### Acknowledgements

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### References


Influence on wide-angle metasurface doublet due to different types of all-dielectric metasurface

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Abstract
We compare the incidence angle dependence among three types of subwavelength structures in all-dielectric polarization-insensitive metasurfaces through electromagnetic simulations. As a result, the waveguide-type metasurface was found to be most suitable for wide-angle metalenses. Therefore, we performed full-wave electromagnetic simulations of cylindrical doublet metalenses to compare the influence on lens performance between micropost-type metasurfaces and waveguide-type metasurfaces. These results indicate that the waveguide-type metasurface improves the lens performance of the doublet lens previously introduced.

1. Introduction and Transmittance of the subwavelength structures for oblique incident light
The oblique incident features of the metasurface are important for the lens applications. Arbabi et al. introduced the doublet metalens with Strehl ratios up to and beyond 0.9 with incidence angles of 25° [1]. The doublet metalens consists of two metasurfaces, the first one is called the correcting lens and the second is called the focusing lens. Their results indicate that the metasurface can be expected to work well even at oblique incidence. Although various types of subwavelength structures for all-dielectric metasurfaces have been designed, the differences in behavior of these subwavelength structures at oblique incidence and the influence on lens performance have not been reported. Lalanne et al. classified them into three types: Waveguide-type, resonant-type micropost and resonant-type nanodisk [2]. We calculate numerically how the transmittance and phase change with increasing angle of incidence for representatives of the three types of structures [1, 3, 4] by Rigorous coupled-wave analysis (RCWA).

We show the results for TM-polarization in Fig. 1. Preferred properties for metalenses are that the transmittance is unity, and covering the whole 0-to-2π phase shift range as the width of the pillars change and that the transmittance and the phase does not change when the incident angle increases. Our representative waveguide-type metasurface kept transmittance about 90% or higher except for a narrow dip at 200nm width at 30deg, and the phases for the oblique incident are close to the values of the normal incidence. On the other hand, micropost-type and nanodisk-type structures do not provide the desired performance. From these results, the waveguide-type metasurface can improve the lens performance comparing to the micropost-type metasurfaces that were used in the Arbabi’s doublet metalens [1]. We confirm that result by performing full-wave electromagnetic simulations of the cylindrical doublet metalens in the next section.

Figure 1: Incident angle dependence of (a), (c), (e) transmission coefficient and (b), (d), (f) the phase from an infinite 2D array of subwavelength structures. (a), (b) Waveguide-type structure [3]. (c), (d) Micropost-type structure [1]. (e), (f) Nanodisk-type structure [4]. All the polarizations of incident light are TM.

2. Cylindrical doublet lens simulations
We use the lens designed by Arbabi et al. (see Supplementary Table 1 in [1]) for our simulations. The lens size is larger than 1mm³, which is too large to perform full vector simulations with wavelength λ = 850nm. It is tempting to reduce the calculation load by performing simulations with reduced lens size, but then the wavefront aberrations are...
Figure 2: Wavefront error after the focusing lens metasurface. (a) waveguide-type metalens at normal incidence. (b) Arbabi’s micropost-type metalens at normal incidence. (c) waveguide-type metalens at an oblique incidence of 30deg. (d) Arbabi’s micropost-type metalens at an oblique incidence of 30deg. Green lines are the OPD wavefront aberrations calculated by Ray tracing. All the polarizations of incident light are TM.

also decreased in proportional to the lens size, and underestimate the wave aberrations. The lens, therefore, should be simulated in the same size as we use in practice to estimate the lens aberration. Our simulations of mm size lens are performed by combination of the finite-difference time-domain method (FDTD) and Rayleigh-Sommerfeld diffraction calculation, which is often used in scalar diffraction calculations [5], and cylindrical lens configuration is used to reduce the calculation time and computer resources. These simulations can estimate the lens performance on meridional plane of a rotationally symmetric doublet lens. Fig. 2 shows the wavefront error for the micropost-type and waveguide-type just after focusing metalens. Optical path difference (OPD) aberrations, as calculated by ray tracing, are also plotted. We can see that wavefront errors of our full vector simulations are in good agreement with those by ray tracing except for random fluctuations. As for the differences between the types of subwavelength structures, there is no significant difference between the two types at normal incidence, but at an oblique incidence of 30°, much larger random fluctuation on wavefront aberration is observed for the micropost-type.

3. Discussion

While approximate wavefront aberrations can be predicted by Ray tracing for both metalens types, the amount of random fluctuation is different at oblique incidence angles. These results are considered to be related to the incident angle dependence of the structure in Fig. 1. The wavefront with large random fluctuation results in reduced focusing efficiency and increased flare and therefore, poorer imaging quality.

4. Conclusions

We investigated the incident angle dependence for three types of subwavelength structures in metasurface cylindrical lens. The simulations were performed for waveguide-type and micropost-type metasurfaces. The simulations show that the waveguide-type metasurface is more suitable for the lens applications with respect to reduced focusing efficiency and flare.

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References


Broadband vectorial ultra-flat optics with up to 99% experimental efficiency in the visible

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Abstract

We propose a methodology that allows the production of high efficiency (up to 99% in the visible) ultra-flat (down to 50 nm thick) optics for vectorial light control and for arbitrarily defined broadband input-output responses of a desired wavefront shape. Experimentally, we show basic transmission/reflection components such as polarizer beam splitters and dichroic mirrors can be manufactured with over 90% efficiency across the visible and present the basis for a two sub-pixel flat optics display.

1. Introduction

Flat-optics has attracted enormous interest as a technology that promises to replace traditionally bulky and expensive optical components with highly integrated nanostructured surfaces [1], [2]. In the visible range however, the efficiency of these devices typically ranges between 20% and 67% [3], [4]. This low efficiency is often the result of a reliance on propagation phase shifts in truncated waveguide designs for operation in the visible, which leads to absorption induced losses [3], [5].

In this work we leverage on a hidden network of universal approximators, which exist in the physical layer of suitably engineered semiconductor nanostructures, to produce flat optics devices capable of reproducing arbitrary optical responses. We employ an inverse design parallel software that combines large scale optimization techniques with the latest generation of neural networks for machine learning in computer vision [6], [7]. Given the desired optical response the software is capable of generating the geometry that produces such a response.

We experimentally validate this approach by manufacturing a variety of common optical components in a flat optics form factor that exceed 90% operational efficiency over the full visible range. We demonstrate devices capable of simultaneous operation in transmission and reflection such as polarizing beam splitters and dichroic mirrors, and the basis of a display technology that produces color images with only two sub-pixels. All devices are produced using a CMOS compatible process and are industry ready for mass production at inexpensive costs.

2. Results

We design, fabricate, and characterize multiple different structures though our platform. In all cases, the devices are produced using the same CMOS compatible manufacturing processes consisting of patterning a layer of amorphous silicon grown on a transparent glass substrate.

We considered first a series of devices for polarization control in both transmission and reflection. Figure 1a shows a summary of the current state of the art in flat optics polarizers. Currently, existing dielectric flat optics designs provide polarization filtering in transmission. In the visible range the best reported efficiency is below 65%, limited by absorption losses in hundreds of nanometers thick material. We demonstrate designs across the visible spectrum, centered at common laser line wavelengths, that exhibit efficiencies in excess of 96% and are capable of simultaneous operation in both transmission (T) and reflection (R). Figure 1b shows the polarization efficiencies, defined as \[ \eta = \left( \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{max}} + T_{\text{min}}} \right) \] for each produced device along with the thickness of the produced structures. Figure 1c shows an SEM image of a nearIR 900 nm centered polarizer designed by our platform. The multiple boxes repeating structure is the result of constraining the software to the use of simple geometries for fabrication simplicity.

Figure 1d reports a comparison between the designed and experimental responses of a flat optics dichroic mirror. The red and blue circles signal the transmission and reflection targets respectively. To the best of the authors knowledge this is the first implementation of a dichroic mirror using flat optics.

Figure 1e presents the design results behind a flat optics color display technology. Existing display technologies, such as LCD, rely on three sub-pixels to produce color images. In this scheme each of the three units is intended to display a specific, fixed primary color. By manipulating the intensity of the light that each unit displays, a gamut of colors may be displayed to the observer. We propose the use of a two sub-pixel based display technology. Two polarization dependent color filters are designed with our platform, one intended to vary between the transmission of blue and green light, and another intended to vary between blue and red. Using a variable intensity light source in combination with a linear polarizer and a liquid crystal cell, a pixel can
be constructed capable of displaying the gamut spanned by RGB colors from just two elements. An example gamut of the colors that can be achieved is shown in the 1931 CIE colorspace at the bottom of this panel. The bold black lines represent the gamut achieved by the individual structures as the polarization is rotated while the black polygon encloses the gamut that can be generated by their combination.

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References

Designing Scattering Properties of Metasurfaces

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Abstract
Metasurfaces have been shown to enhance the Local Density of Optical States (LDOS), providing large improvements in the power emission of dipole emitters. Many experimental works have focused on the properties of metasurfaces composed of square arrays of scatterers. In this work, we develop a method of designing metasurfaces to produce the desired scattering properties, focusing on the application to antenna design. Using this method, we demonstrate a three-fold improvement in the LDOS compared to a square array.

1. Introduction
The radiation properties of a dipole emitter can be controlled by changing the environment around it [1, 2]. This is due to a modification of the local density of optical states (LDOS), which is the number of electromagnetic modes per unit volume, per unit frequency at a given point in space [3]. According to Fermi’s Golden Rule

\[ \Gamma_{i \rightarrow f} = \frac{2\pi}{\hbar} |M_{f,i}|^2 \rho(E_f), \]

where \( \Gamma_{i \rightarrow f} \) is the transition probability, \( M_{f,i} \) is the matrix element linking the final and initial states, and \( \rho(E_f) \) is the density of final states.

Recent experimental work has demonstrated that metasurfaces comprising several discrete scatterers have the potential to greatly improve photoluminescence by coupling emitters to Mie resonances [4], as well as modifying the angular distribution of light scattering by selectively combining Mie resonances [5].

Aiming to exploit the potential shown by these materials, methods of optimizing metasurface design have been developed. These including evolutionary algorithm approaches, working with discrete scatterers [6] and methods based upon perturbation theory to grade continuous structures [7].

In this work we build upon this: applying a perturbative approach to optimizing the power emission of a dipole emitter near a metasurface of scatterers. Analytically, the effect of moving a scatterer upon the LDOS is calculated, then the metasurface optimize numerically. Our design based approach may find utility in improving on the already promising experimental results obtained from Mie resonant metasurfaces [4, 5], as well as in designing antenna directionality by allowing for multiple feeds and acoustics [8].

2. Discussion
Making use of the fact that a small antenna may be treated as a point dipole, and small scatterers can be treated as points so long as their radius \( R \) is small compared to the wavelength of light \( kR \ll 1 \); we have solved Maxwell’s equations for point current and polarization sources in terms of the free space Green’s function [3] where each

Figure 1: Initial and final configurations of the array of 196 electric dipole scatterers, indicated by white dots, with a radiating dipole indicated by a star at the origin. Colour indicates phase of the electric field, and brightness magnitude.
scatterer supports a combination of electric and magnetic dipole moments, given by \( p = \alpha_E E \) and \( m = \alpha_M H \) respectively [9]. According to Equation (1), to improve the radiated power of the dipole emitter, we must increase the LDOS at the location of the emitter [3], given by

\[
\rho_p(e_d, r_0, \omega) = \frac{\omega}{2} \Im \left[ e_d \cdot E(r_0, r_0) \right],
\]

where \( e_d \) is the polarization of the radiating dipole. In order to optimise this quantity, we have calculated the first order correction to the electric field under a small perturbation to the location of one of the scatterers \( r_n \to r_n + \delta r_n \). Numerically, we use an adjoint algorithm to perform an optimization on large, but finite, arrays of scatterers. This has the benefit of giving the field at all of the scatterers simultaneously, and being fully transparent in its operation. For each point, the first order correction is calculated, then combined with Equation (2) to give a step size and direction that the scatterer should take to increase the LDOS at the location of the emitter.

As a simple initial configuration, we apply our algorithm to an array of 196 scatterers, with \( \alpha_M = 0 \), and \( \alpha_E \) chosen to match the extinction and scattering cross-sections of silicon nano-spheres of radius 65 nm. The radiating emitter is placed in the plane of the metasurface. Fig. 1 shows how the locations of the scatterers evolve over the optimization procedure, and Fig. 2 demonstrates that a three-fold power improvement can be obtained from this procedure.

3. Conclusions

The rate of power emission of a dipole emitter is governed by the LDOS (2), which can be modified by the environment surrounding the emitter. Using metasurfaces composed of several discrete scatterers has been experimentally shown to enhance the LDOS in a range of systems [4, 6], modifying radiation properties. In this work we propose a technique, based on perturbation theory, to design the scattering properties of metasurfaces. As a first step, we apply this to a metasurface of electric dipole scatterers, and demonstrate a three-fold improvement to the LDOS, compared to a square array. Future work includes applying this method to engineer other radiation properties, such as directivity by optimizing different scattering properties at different feed points.

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References

Ion-beam-doped transparent conductive oxides for metasurface applications

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Abstract

Doped transparent conductive oxides have gained a lot of attention for applications in plasmonics and nanophotonics due to their low optical loss, metal-like behavior, tailor able optical properties, and well-established fabrication procedures. N-type doped zinc oxide, like gallium-doped ZnO is attractive because its permittivity can be engineered over a broad wavelength range across the infrared.

Here, we demonstrate how the optical properties of ZnO can be modified by doping with gallium using a commercial focused ion beam system and post-implantation annealing.

1. Introduction

ZnO can be heavily doped to exhibit metal-like optical properties in the near-infrared wavelength range. Large area ion implantation combined with suitable lithography techniques or selective ion irradiation with a focused ion beam (FIB) system might be used to fabricate ultra-thin plasmonic devices based on gallium doped ZnO (GZO). For example, subwavelength structure elements such as GZO nano disks may be prepared in an undoped ZnO matrix to fabricate frequency selective surfaces (FSSs).

Our finite-difference time-domain (FDTD) simulations show that a 20-nm-thick FSS based on a pattern of GZO nanodisks can be used as a spectral filter or frequency-selective thermal emitter, with the central wavelength determined by the FSS geometry and the carrier concentration. For example, a disk diameter of 500 nm, a period of 600 nm, and a local free-carrier concentration of $5 \times 10^{20}$ cm$^{-3}$ give us a central wavelength of around 6 μm.

2. Experimental

Single crystalline $<001>$ ZnO substrates were irradiated with 30 keV Ga$^+$ ions at room temperature using a commercial FIB system. For our implantation conditions the maximum penetration depth of gallium in ZnO was estimated with SRIM calculations to be 20 nm [1]. On each sample, several $200 \times 200 \mu m^2$ areas were homogeneously implanted with ion fluences ranging from $N_i = 1.15 \times 10^{14}$ to $N_i = 6 \times 10^{15}$ cm$^{-2}$. These fluences correspond to a Ga concentration of 0.1 at% to 6 at%, which is close to and above the solid solubility of Ga in ZnO (0.5 at% [2, 3]).

For comparison, large area (1 cm$^2$) ZnO substrates were homogeneously implanted with 30 keV Ga$^+$ ions using a 400 kV implanter and with the same fluence range used for the FIB irradiations in order to perform ellipsometry analysis. To heal the ion-beam-induced disorder in the ZnO crystals and to activate the gallium dopants onto zinc lattice sites, post-implantation annealing was performed at 600 – 1000 °C for 40 minutes in air, respectively.

3. Results and Discussion

We used a Fourier-transform infrared (FTIR) spectrometer to measure the changes in optical reflectance and transmittance induced by the ion irradiation (see figure 1).

![Figure 1: FTIR transmittance measurements of FIB gallium implanted single crystal ZnO for selected ion fluences and annealing temperatures.](image)

Intrinsic ZnO has a high transmittance up to 9 μm. With increasing gallium-ion fluence, the transmittance in the as-implanted state decreases. This decrease is presumed to be caused by an increasing amount of lattice defects due to the ion implantation. Annealing at 600 °C leads to a strong reduction of defects in the ZnO. Thus, the transmittance spectra of ZnO after annealing at this temperature are
comparable with the intrinsic ZnO spectrum [4]. A further increase of the annealing temperature to 900 and 1000 °C decreases the transmittance again. This might be attributed to gallium dopants incorporated on zinc lattice sites, which leads to an increase in the carrier concentration and thus a reduction of the transmittance.

To characterize the optical properties of our homogeneously implanted ZnO samples, we performed spectroscopic ellipsometry (Fig. 2).

The experimental data of Ψ and Δ of our GZO were fitted with a 2-layer model: a semi-infinite ZnO substrate and a surface layer for the GZO. A Drude-Lorentz (DL) oscillator model was used to describe the complex permittivity of the GZO layer. Figure 2 (a) shows that the measured Ψ of intrinsic ZnO and GZO (6 at%), which was annealed at 600 °C and 700 °C, show no difference. Therefore, the optical properties of these samples are still comparable to intrinsic ZnO. However, annealing above 700 °C results into large differences in Ψ and Δ compared to intrinsic ZnO. Figure 2 (b) shows the experimental and fitted data for GZO (6 at%), which was annealed at 1000 °C. The model fits and experimental data are in good agreement. However, the fitted GZO layer thickness is much larger than expected. The differences likely originate from the simplified assumption of a box-like doped ZnO layer, neglecting the gaussian doping profile and strong gallium diffusion. Figure 2 (c) summarizes the real and imaginary parts of the permittivity for intrinsic ZnO and annealed GZO (6 at%). With increasing annealing temperatures, ε₁ decreases while ε₂ increases. This might be an indication of dopant activation in a rather thick GZO layer.

Additionally, the reflectance spectra of GZO were calculated using the fitted parameters of intrinsic ZnO and doped GZO and using FDTD-simulations. The simulated and measured FTIR reflectance spectra are compared in Fig. 3 and show relatively good agreement. Drude-metal-like behavior with high reflectivity is observed only for the highest doping concentrations and for wavelength larger than 8 μm. The fitted thickness of the GZO layer as a function of annealing temperature is shown in the inset of Fig. 3. With increasing annealing temperature, the thickness of the optically active GZO layer increases from initially ~ 20 nm to more than 2 μm, due to thermal diffusion of gallium.

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References

Accurate Circuit Model for Periodic Array of Square Patches

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Abstract

A novel circuit model for the grid impedance of electrically dense arrays of subwavelength metallic square patches is derived using analytical formulas for arrays of metallic square holes. The circuit model consists of shunt connection of inductors and capacitors whose values depend on the square patch geometry and can predict resonance frequency of arrays of square patches. Analytical formulas were derived for the model elements by applying combining the results previously obtained for arrays of metallic square holes with the approximate Babinet principle for frequency selective surfaces (FSS). By comparison with full-wave simulations, we show that the model can predict the reflection and transmission of FSS with high accuracy.

1. Introduction

A frequency selective surface (FSS) consists of a periodic array of conducting elements such as square patches or stripes that are usually mounted on a dielectric layer, and show resonant behavior. FSS arrays have many applications including artificial dielectrics [1], planar reflect-arrays [2], artificial high-impedance surfaces [3], and transparent conducting electrodes [4].

Analysis of FSS structures has been carried out by various numerical and analytical techniques. Numerical methods are general and appropriate for complex and arbitrary structures [5]. But for a simple shape, like a square patch, using analytical techniques such as the equivalent circuit method is convenient and fast [4], [6]. In equivalent circuit methods, FSS is modeled by shunt and series connections of inductive or capacitive elements whose values depend on the geometry of the FSS and the underlying substrate. Besides being simple and fast, this approach provides physical insight into critical parameters and effect of shape and geometry of the FSS on it’s electromagnetic response.

For an array of square patches an equivalent circuit model was developed in [6]. This model works properly at low frequencies when square patches behave like a purely inductive or capacitive component, but does not predict resonance phenomena. The circuit model developed in [7], on the other hand, fails when the gap between elements is nearly zero.

In this paper we provide a reliable and simple analytical model for arrays of square patches by using the approximate Babinet principle for FSS structures and analytical formulas that were previously derived for arrays of metallic square holes [4]. This model can predict FSS behavior until its first resonance with high accuracy.

2. Circuit model and grid impedance

Consider a 2-D infinite array of square holes in a perfectly conducting sheet along the x and y-axes as in Fig. 1. For the sake of simplicity, we consider the medium which surrounds the structure to be free space. According to [8] this structure can be represented by a circuit model that is shown in Fig. 2 where \( Y_0 \) is free space admittance and \( Y_s \) is given by

\[
Y_s = \sum_{m=1}^{\infty} 4 \left( \frac{1}{Z_{00}} \right) k_{mn} + \sum_{m=1}^{\infty} 4 \left( \frac{1}{Z_{00}} \right) k_{mn} + \sum_{m=1}^{\infty} 8 \left( \frac{m\pi a}{n^2} \right) \text{sinc} \left( \frac{ma}{a} \right)
\]

Where

\[
A_{mn} = \frac{2d^2 \cos \frac{m\pi a}{n^2}}{a^2 - 4a^2 n^2} \text{sinc} \left( \frac{ma}{a} \right)
\]

\[
Z_{mn} = \frac{\omega \mu k_{mn}}{\varepsilon}
\]

\[
\gamma_{mn} = \frac{k_{mn}}{\varepsilon}
\]

Here \( \omega \) is the angular frequency, \( k_{mn} \) is the wave-vector component of the diffraction orders along the \( \vec{z} \) direction, \( \varepsilon, \mu \) is the permittivity and permeability of the free space, respectively.

Fig. 1. A 2-D infinite arrays of metallic square hole

\[
\text{Fig. 1. A 2-D infinite arrays of metallic square hole}
\]
Let
\[ Z_s = \frac{1}{Y_s} \]  
\[ Z_s' = \frac{\eta_0 d}{4Z_s} \]  
where \( \eta_0 \) is the free space impedance. It is worth noting that this analysis can be extended to more complex structures such as high-impedance surfaces.

3. Validation
We compare the proposed analytical circuit model and the model in [6] with simulations performed using full-wave electromagnetic simulation software (CST). To analyze the infinite array of square patches, periodic boundary conditions were used along the x-y plane. The geometrical parameters of the square patches (the structure complementary to Fig. 1) are \( d = 12 \text{mm}, \ a = 5 \text{mm} \). The thickness of the metal patches is assumed to be zero. The transmission coefficient of the structure is shown in Fig. 3. It is clear that the model in [6] fails near the resonance frequency. The model proposed works with high accuracy even after the first resonance.

4. Conclusions
In this paper, we used an analytical formula to drive a simple circuit model for an infinite array of square patches that accurately accounts for the first resonance of the structure. Comparison with full-wave simulation results show good agreement unlike previously derived models. The model presented can be extended to more complex structures by considering different media that surround the square patches.

References
High Efficiency Titanium Dioxide Huygen’s Metasurfaces In UV

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Abstract
Metasurfaces possess the capability to manipulate multi aspects of light and have been used to demonstrate wavefront engineering devices. In this project, we choose Huygens’ metasurfaces with high efficiency and small thickness to wavelength ratio to achieve wavefront shaping. Overlap of electric and magnetic resonances in titanium dioxide nanodisk employs Huygens’ condition which gives our device a full phase coverage and close unity transmission in UV. Such properties enable an efficient light focusing flat optical device.

1. Introduction
By tuning the structural parameters (size, shape, periodicity etc), metasurfaces possess tunable optical properties superior to conventional material that is restricted to their intrinsic properties. While plasmonic metasurface had been utilized for wavefront engineering applications [1-5], using a dielectric metasurfaces avoids the problem of metal’s lossyness. A variety of optical components ranging from IR to visible region, such as lenses, holograms and gratings devices, is demonstrated using silicon-based metasurface [6-10]. In this work, TiO2 nanodisk metasurface is feasible in UV region due to its low loss properties. To gain a full control of wavefront, 2π phase coverage must be obtained. In [11-14], dielectric nanostructure is treated as truncated waveguide for wavefront shaping. Such approach requires high aspect ratio structures to accumulate 2π phase shift. Since Huygens’ condition is achieved by resonance behavior, our metasurfaces can be ultrathin, thickness to wavelength ratio=0.2, the fabrication difficulty is reduced. High transmittance emitting of Huygen’s source implies a potential high efficiency optical device. Other work had demonstrated Huygens’ surfaces with metallic structure at microwave frequency [15] and dielectric material for NIR [16] and optical frequency [17].

2. Discussion
2.1. Approach
Radiation of each Huygens source could be presented by the emission small antenna that radiates far-fields of crossed electric and magnetic dipole. The combination of radiation pattern of an electric and magnetic dipole gives a unidirectional forward transmittance. Both dipoles are generated by simultaneous generation of Electric and magnetic and resonance at designed wavelength. 2π phase coverage can be realized with summing up two π’s each given by electric and magnetic resonance.

2.2. Simulation
We employed finite element method (FEM), COMSOL Multiphysics software to design our metasurface. In our simulation setup, construct a periodic array of TiO2 nanodisk with height of 80nm and period of 240 nm in a homogenous medium having a refractive index of 1.3. Simulation result of transmittance Fig. 1(a) and phase Fig. 2(b) spectrum of a nanodisk with radius of 88 nm qualifies for a Huygens surface. The 88 nm radius nanodisk shows a close to unity transmittance at frequency of 784 THz, wavelength of 382 nm, due to overlapping of magnetic and electric resonant illustrated in. It is obvious that the nanodisk possess 2π phase swift. A contour mapping of transmittance and phase is given in Fig. 1(c) and (d). At 784 THz frequency, high transmittance is maintained throughout different radius while full 2π phase range is covered. From above, we can expect that TiO2 metasurfaces have the potential for achieving high efficient focusing device.

Figure 1: (a) Transmittance (b) Phase spectra of TiO2 nanodisk with radius of 88nm. (c) Transmittance and (d) phase contour of different diameter TiO2 nanodisk.

The electric and magnetic field distribution of TiO2 nanodisk is shown in Fig. 2. From the field distribution, we
can clearly identify electric and magnetic dipole confined within the nanodisk structure.

![Image](image_url)

**Figure 2**: (a) Electric and (b) magnetic field distribution of TiO2 nanodisk metasurfaces with radius of 88nm at 784THz.

### 2.3. Fabrication

We utilize fabrication processes well known in semiconductor industry to realize our design. The complete flow is presented in Fig. 3(a). First the electron beam lithography is done on silica substrate to define pattern using A4 PMMA photoresist. After development of photoresist, we deposit TiO2 on by electron gun evaporation. Next, the undeveloped photoresist is lifted off using acetone in result establishing our nanodisk structure. Finally, by applying SOG (spin on glass), the TiO2 metasurfaces are embedded in a homogenous medium. Preliminary result of fabricated nanodisk Fig. 3(b), ensures such structure can be done by liftoff process.

![Image](image_url)

**Figure 3**: (a) Experiment flow of fabricating TiO2 metalens (b) SEM image of TiO2 nanodisk coated with Pt

### Conclusions

In simulation, TiO2 nanodisk metasurfaces structure is confirmed to withhold electric and magnetic resonance at same frequency. This gives an extra $\pi$ swift compare to a single resonant and a high transmittance. We have preliminary experiment result of nanodisk structure. In future, we will conduct optical measurements.

### Acknowledgements

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Enhanced Evanescent Field Confinement Driven by Bound States in the Continuum

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Abstract
Here, the enhancement of electromagnetic field confinement in an all-dielectric metasurface is demonstrated. The enhanced confinement is achieved when the polarization singularity, corresponding to accidental bound states in the continuum, moves to the domain of evanescent fields (under the light line). Such a hybridization of the bound states and evanescent waves results in the 70-fold increase of the electric field enhancement on the top of the metasurface and boosting of the electric field localization.

1. Introduction
Metasurfaces and meta-gratings are one of the cornerstones of the modern photronics due to the high versatility of their physical and, specifically, optical properties. Since the very famous work by John Pendry in 2000 [1], the photonics of metasurfaces has got boost, and currently metasurfaces are utilized for signal modulation [2], information processing [3], color printing [4], surface-enhanced Raman scattering [5] and sensing [6]. Sensing by metasurfaces is of particular interest because of the capability of these nanostructures to confine and enhance optical fields as well as their high figure of merit [7]. Biosensing and single-molecule sensors based on metallic (plasmonic) metasurfaces have been demonstrated in several works [8], and the ability of surface plasmons to confine light makes them perspective for the practical applications. However, due to the high dissipative losses in metals in the optical range, this technology has not yet reached the industry [9].

Recently, new approaches which utilize high-Q modes in all-dielectric metasurfaces have been established [10]. The origin of such the high-Q modes has been discovered as bound states in the continuum (BIC) [11]. In theory, the Q-factors of BICs can be infinitely large, and the electric field enhancement can be respectively high [11]. Such a unique property of BIC originates from the physical symmetries of metasurfaces (parity and time) and results in cancelation of radiation in the far-field at the certain point of band diagram of the metasurface. At the same time, macroscopic dielectric structures in the waveguide regime, e.g. planar waveguides and optical fibers, are widely used in optical sensors.

Our work aims to combine unique properties of metasurface BICs and waveguides giving rise to the electromagnetic field confinement in the optical mode of a metasurface. By varying the geometrical parameters of the metasurface we achieve BIC transition under the light cone and boosting the field confinement of the waveguide mode. This approach is based on cancelation of certain Fourier term in electromagnetic field expansion of the metasurface mode.

2. Results and discussion
First, we consider a GaP meta-grating based on rectangular meta-atoms (see Fig. 1(a)) located at a quartz substrate. Notefully, such the mirror-symmetry shape of meta-atoms presumes both $\Gamma$- and off-$\Gamma$ BICs. We adjust the metasurface geometrical parameters to operate in near-IR spectral range. The refractive index of the metasurface is 3.143, the refractive index of the substrate is 1.452. The height (H) of the metasurface is set to 370 nm at the first calculation step. The metasurface is surrounded by air.

Figure 1: (a) A sketch of the metasurface operating in hybrid BIC-waveguide regime. (b) Band structure of the metasurface. H-parameter is tuned to tune the BIC under
the light line of the air (yellow area).

Next, we calculate band structure of the metasurface using COMSOL Multiphysics (Fig. 1(b)). The green area corresponds to the radiation continuum above the light line of air. Yellow area is below the light line of air and above the quartz light line. Blue area designates the zone below the light line of quartz. The optical mode under consideration is distinguished by red. Initially, we observe the BIC in the green area simultaneously tracking the electric field distribution of the mode in the yellow area (Fig. 2(a)). It is clearly seen that, while the BIC is located in the radiation continuum of both air and quartz, the mode in the semi-waveguide regime gives 5-fold enhancement at the top of the metasurface and possesses long tails outside the rectangles.

Figure 2: Electric field distributions of the optical mode of the metasurface in semi-waveguide regime at (a) $H = 370$ nm and (b) $H = 400$ nm.

Finally, we vary the height of the metasurface ($H$) in order to tune the BIC location in the band diagram. After several optimization cycles, we have found that the increase of $H$ from 370 nm to 400 nm moves BIC under the light line of the air (see Fig. 1(b), blue arrow). Such a band diagram transition immediately reflects in the electric field distribution of the mode in semi-waveguide regime (Fig. 2(b)). It can be observed that the electric field enhancement in the hybrid BIC-waveguide regime is increased by 70 times, and the mode tails in the free space are shortened comparing with the Fig. 2(a). Other words, the electric field confinement of the waveguide mode gets boost after transition of BIC below the light line in the waveguiding area of the band diagram.

The presented electromagnetic confinement enhancement owes to the magnification and suppression of certain Fourier terms in the Fourier expansion of the electric field of the mode. The radiation cancelation in BIC is due to the suppression of zero Fourier term while the same term in the waveguide or semi-waveguide regime is partially responsible for the field confinement. Thus, after BIC transition below the light line, the waveguide mode obtains this expansion feature of BIC, and the zero terms gets canceled. In this case, the mode confinement is mostly determined by the first Fourier term which is characterized by the fast exponential decay of the field outside the metasurface.

3. Conclusions

To conclude, we have demonstrated the enhancement of electromagnetic field confinement in the all-dielectric metasurface. The confinement growth owes to the transition of BIC below the light line in the waveguiding area. We have shown that this transition results in 70-fold increase of the electric field and shortening of the mode tails.

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References


Dynamic Optical MEMS Metasurfaces

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Abstract

We present a versatile platform for achieving dynamical metasurfaces by combining micro-electro-mechanical systems (MEMS) with plasmonic nanostructures. By varying the separation of a gold piezoelectric MEMS mirror and gold nanostructures we adjust the behavior of the reflective metasurface. The concept is demonstrated for several cases, including switchable gratings and lenses. Few optical MEMS metasurfaces have been demonstrated previously, and this platform has the advantage of allowing full freedom in the metasurface design as well as decoupling MEMS and nanostructure fabrication.

1. Introduction

This summary and the corresponding presentation are based on work presented in detail in [1].

In recent years there has been a growing interest in metasurfaces in general and increasingly also for metasurfaces with tunable functionalities [2]. To be able to change how the metasurface interacts with light many different approaches are being investigated, including metasurfaces with phase transitions [3,4], electrical doping (often with graphene) [5,6], liquid crystals [7] and MEMS [8]. The different approaches have their own advantages and disadvantages, for example concerning modulation efficiencies, response times and polarization control [9].

We demonstrate a switchable gap surface plasmon (GSP) based metasurface [10] by combining gold nanostructures with a gold MEMS mirror [11]. This platform has the advantage of being easy to implement and adapt for various purposes, as the metasurface and MEMS mirror can be designed and fabricated separately.

2. Design and fabrication

The design is based on previously demonstrated GSP metasurfaces [10] in which gold nanostructures are separated by a thin layer of dielectric media (usually less than 50 nm) from a gold substrate. By replacing this gold substrate with a movable MEMS mirror and the dielectric spacer with an air gap, the resulting device can be tuned by adjusting the separation between the nanostructures and mirror. To demonstrate the concept, we designed several metasurfaces that were optimized to work as blazed gratings and as focusing lenses for light with 800 nm wavelength at an air gap of 20 nm between the gold nanostructures and mirror.

The gold nanostructures were fabricated on glass using EBL, and these glass slides were subsequently glued to gold piezoelectric MEMS mirrors [11], such that the separation between the nanostructures and mirror could be controlled by actuating piezoelectric membranes.

3. Results

After mounting the glass slides to the MEMS mirror, the air gap between the glass and mirror was measured by analyzing the interference patterns of light at two wavelengths (495 nm and 532 nm), originating from reflections between the mirror and glass. Typical separations before actuating the mirror were around 2 µm, within range of the mirrors that can be displaced around 6 µm. Particle contaminations on the mirrors and glass substrates made it challenging to achieve the small air gaps the metasurfaces were designed for. However, by fabricating the nanostructures on top of 10 µm pedestals on the glass slides, as well as fabricating several samples, we were able to achieve air gaps of around 50 nm between the nanostructures and mirror. It is important to note that these issues are not expected to be a problem if one is manufacturing these devices on the wafer scale in a single cleanroom fabrication line.

For the devices that achieved 50 nm air gaps we were able to measure efficiencies of around 50% for both beam steering and beam focusing metasurfaces and demonstrate the tuning of these functionalities by actuating the MEMS mirrors [1].

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References


Metasurfaces with Maxwell’s demon-like nonreciprocity

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Abstract

Compared to reciprocal systems, the designs of Lorentz non-reciprocal metasurfaces and metamaterials require extra complexity associated with many broken symmetries. We provide minimal designs of Lorentz non-reciprocal metasurface and arrays made of simple dimer unit cells. We show that Maxwell’s demon-like nonreciprocity can be supported in a class of non-Hermitian gyrotropic metasurfaces in the linear regime. The proposed metasurface functions like a transmission-only Maxwell’s demon operating at a pair of photon energies. Based on the multiple scattering theory, we construct a dual-dipole model to explain the underlying mechanism that leads to the antisymmetric nonreciprocal transmission. The metasurface’s effective medium parameters are also obtained.

1. Introduction

Unconventional phenomena could emerge in metamaterials using the internal structural properties of the artificial unit cells. Recently, designs of complex structures made of Lorentz non-reciprocal materials have introduced many new directions to create unusual photonic devices such as isolators, one-way waveguides, and non-reciprocal antennas. Analytical modeling of these complex systems is not trivial and many designs such as topological photonic crystals are bulky. We aim at reducing the thicknesses and sizes of the non-reciprocal metasurfaces and devices while maintaining the simplicity of the structures.

2. Methodology

We use coupled dipole-monopole theory to design a “diatomic” metamolecules consisting of two cylinders with at least one of the cylinders made of gyromagnetic/gyroelectric materials. The functional performance of the metasurface design is also verified numerically using the commercial software COMSOL. Finally, we have used an effective medium theory to describe the metasurface design.

The analytical results are based on coupled dipole-monopole theory, which expands the fields of each cylinders using multiple expansion up to dipoles. The coupled dipole-monopole equations are written as a 2x2 matrix equation in the form as shown below:

\[
\begin{pmatrix}
-b_{y_2}^2 & 0 \\
0 & -b_{y_1}^2
\end{pmatrix}^{-1} - \begin{pmatrix} I_1 & 0 \\ 0 & I_2 \end{pmatrix} \begin{pmatrix} a_{y_2}^2 & 0 \\ 0 & a_{y_1}^2 \end{pmatrix} = \begin{pmatrix} a_1 \alpha \\ a_2 \alpha \end{pmatrix}
\] (1)

where a rotating magnetic dipole \((m = -1)\) is coupled to a monopole \((m = 0)\) through long-range dynamic coupling.

3. Results

The schematic of our design is shown in Figure 1(a). The associated numerical and analytical results for the difference in transmittance \((\Delta T = T_1 - T_2)\) between forward and backward incident waves are shown in Fig. 1(b). Simulated field patterns at one of the peak-dip pair is shown in Fig. 1(c).

Figure 1: (a) Schematic of Lorentz non-reciprocal “diatomic” metasurface. (b) Transmission difference between forward and backward incident waves. (c) Simulation field patterns for the same case as in (b).

4. Conclusions

In summary, we propose an ultra-thin metasurface that can produce an anomalous antisymmetric nonreciprocal transmission peak-and-depth pairs. The metasurface functions like an imperfect Maxwell’s demon for normal incident photons. It is found that the anti-symmetric (non-reciprocal) transmittance is induced directly by the
asymmetrical absorption in lossy dielectric cylinders under the cooperative effect of the rotating magnetic dipole and linear electric dipole excited in the metasurface. Eigen-response theory using a simple $2 \times 2$ matrix truncated from the multiple scattering theory is employed to reveal the underlying mechanism.

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A dielectric metasurface-polarimeter for single-shot detection of arbitrary polarization states

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Abstract
We present a dielectric metasurface using an asymmetric design that exploits exotic multipolar interactions forming polarisation-dependent resonant eigenmodes. We experimentally demonstrate single-shot full-state polarimetry.

1. Introduction
Metasurfaces\cite{1}, the two-dimensional equivalent of metamaterials, comprise subwavelength thick nanostructures (also known as meta-atoms). Judicial design of the geometrical parameters and spatial distribution provide unprecedented control of amplitude, phase, angular momentum and polarization of light. Metasurfaces can provide an ultrathin, robust and compact platform for the measurement of polarization of light, a.k.a. polarimetry. Plasmonic (metal based) metasurfaces for polarimetry have been investigated\cite{2, 3} but suffer from low efficiency due to metal absorption losses. Although inline polarimetry has been demonstrated from a single layer metasurface platform, multiple detectors were needed to measure the polarization\cite{2}. With dielectric metasurfaces, using the either propagation phase (geometrical pillar variation) or the Pancharatnam-Berry phase (accumulated phase from changing the orientation angle of meta atoms), unique designs were realized to measured different polarization state\cite{4, 5}. A method combining two designs incorporating both phases in one design was used to measure any elliptical polarization state\cite{6}. This approach was also extended for indirect detection of polarization state through holography\cite{7, 8} encoded in the metasurface design. However, with holography it’s difficult to get a good resolution as each polarization sensitive hologram has been encoded in the design. Furthermore, the limit for incorporating multiple designs into a single layer is set by the periodicity, which is a major setback to scalability.

Here we introduce an all-dielectric metasurface design comprising of elliptical nanopillars that provide a unique diffraction pattern dependent on the input polarization of light which covers the entire Poincare sphere from a single unit cell design. The elliptical pillars of amorphous silicon (α-Si) of height, \( h \), 520 nm are arranged on a fused silica substrate with light \( \lambda : 810 \text{ nm} \) incident normally from the substrate as shown in Figure 1(A). The period \( p \) is 600 nm (\( > \frac{2 \lambda}{n} \); where \( n \) is the refractive index) enabling (±1,0) and (0,±1) diffracted spots. Figure 1(B) shows two examples of diffraction patterns from \( |H\rangle \) and \( |V\rangle \) polarization states along with the FDTD simulations. We then perform experiments, using a large condenser lens and Fresnel lens, such that a single shot image of the diffraction pattern is obtained on a camera.

2. Discussion
The intensities from the diffraction spots from the various polarization states can be quantified by \(|I|=|M|.|S|\); where the intensity matrix \(|I|\) contains the intensity differences with respect to \(|H\rangle +|V\rangle \) represented as by \( I_{|H\rangle +|V\rangle}^{HV} \) where \( I_{|H\rangle +|V\rangle}^{HV} \) is the intensity of the \( n_{th} \) spot for \(|H\rangle +|V\rangle \) polarization and \( I_{|P\rangle}^{P} \) is the intensity from the \( n_{th} \) spot for \( |P\rangle \) polarization. The Stokes matrix \([S]\) contains the Stokes parameters \((S_1, S_2, S_3)\) normalized to \( S_0 \). The metasurface matrix, \([M]\), is calculated from the intensities of the fundamental orthogonal states. Figure 1(C) shows the Stokes parameters calculated for various polarization states using the metasurface matrix and comparing it with theoretical values. This shows that not only do we observe a unique diffraction pattern for any polarization state – linear, circular or elliptical, but we also resolve any linear polarization state with a resolution of 5°. Circular polarization light is a superposition of orthogonal linear polarized light with a phase offset, thus in principle should not have unique diffraction patterns, yet these too are distinguishable with our single metasurface. One of the reasons we observe a difference is the formation of an anapole state with \(|A\rangle\) polarization incident on the metasurface. The eigenmodes excited for \(|A\rangle\) polarization state are quite different from the orthogonal pair \(|H\rangle\) and \(|V\rangle\). From Figure 1(D) we observe multipolar coupling between the electrical poles and magnetic toroidal poles for the nano pillars shown in the schematic. The toroidal magnetic poles formed axially (with the displacement current vectors along \( \vec{E} \)) interact with the electrical dipole to form a non-radiating anapole state\cite{9}.

3. Conclusions
Thus, we are able to resolve any arbitrary polarization state from the intensity difference of the unique diffraction pat-
and 26 polarization state, which exhibits the formation of an anapole state from the electrical multipoles (E) component for ultra-compact polarimetry and imaging[10], and work consequently introduces an important optical component corresponding to the particular polarization states. Our work consequently introduces an important optical component for ultra-compact polarimetry and imaging[10], and particularly for quantum optics[11, 12].

References

All-dielectric metasurface linear polarizer for visible wavelengths utilizing the first Kerker condition

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Abstract
Polarizers are indispensable elements integrated within a myriad of optical setups across many applications, from imaging assemblies to display technology. Commercially available polarizers are typically characterized by a low damage threshold, low extinction coefficient, and low operating bandwidth. In this paper, we present an all-dielectric metasurface linear visible polarizer with high extinction ratio. The polarizer consists of sub-wavelength titanium dioxide (TiO2) structures which utilize Kerker’s first condition in order to generate the desired transmission response across the visible spectrum. In addition, the reported all-dielectric polarizer has a high damage threshold and can be tuned to different wavebands through geometry modification.

1. Introduction
Polarizers are essential optical elements that play an important role in many optical systems. Most of the available commercial polarizers (film or wire-grid) have various drawbacks including: low extinction coefficients, small clear apertures, narrow operating bandwidth and low damage thresholds. Metasurfaces are arrays of nanostructures with sub-wavelength thickness that can be used to manipulate both the amplitude and phase of the incident light. In recent years, all-dielectric metasurfaces have shown exciting potential for the development of ultrathin highly functional optical elements [1]. In contrast to metallic (plasmonic) metasurfaces, all-dielectric structures respond to both the electric and magnetic fields of light and owe their superior performance to minimal material dissipation losses [2].

In this work, we show an all-dielectric metasurface linear polarizer utilizing Kerker’s first condition. The reported polarizer has an extinction ratio \( 0.f > 2.8:1 \) at the operating wavelength 500 nm. TiO2 is chosen as the meta-element (resonator) material due to its high refractive index with negligible losses in the visible region, unlike conventional high refractive index materials such as Si and GaAs which have high losses [3]. Further, TiO2 is widely used in the thin-film optics manufacturing community, for conventional multi-layer filters.

Dielectric resonators have Mie resonances that exhibit electric and magnetic dipoles. The spectral positions of these dipoles depend on the geometrical parameters of the resonators, and material properties [4]. At particular geometrical dimensions such dielectric resonators exhibit strong forward scattering with almost zero backscattering. This occurs when the electric- and magnetic-dipole resonances have similar strengths and phases leading to a constructive interference in the forward direction, and destructive interference in the backward direction. This phenomena is known as the first Kerker’s condition [5]—which was used here to design the aforementioned polarizer. The geometrical parameters were optimized to satisfy the first Kerker’s condition for x-polarized light showing approximately unity transmission. For y-polarized light, the first Kerker’s was not satisfied leading to low transmission.

2. Results
Fig. 1 shows the schematic for the proposed polarizer. The polarizer is composed of a square array of rectangular TiO2 resonators (patches) on a glass (SiO2) substrate. Each rectangle has a width of 180 nm, a length of 410 nm and a thickness of 120 nm. The array has a period of 500 nm in both x and y directions—optimized through parameter space exploration in simulation.

Figure 1: Schematic of the dielectric metasurface-based polarizer consisting of an array of TiO2 rectangular patches on top of a glass substrate.
The simulation results were performed using Lumerical (Ansys) Finite Difference Time Domain (FDTD) Solutions [6]. The simulated source had two different polarization states including x- and y-polarized waves, with propagation wavevector (z-axis) at normal incidence to the structure surface, as shown in Fig. 1. Periodic boundary conditions were considered in x and y directions to emulate a periodic array while perfectly matched layers (PMLs) were applied in the z-direction. The dispersive refractive index of TiO$_2$ was adopted from [5] while the refractive index for the glass (SiO$_2$) substrate was calculated from the multi-coefficient model within [6].

Fig. 2 shows the simulated transmission results for the proposed metasurface polarizer. The polarizer exhibits >80% transmission for the x-polarized wave across the entire waveband. The high transmission was reached by adjusting and optimizing the geometrical parameters of the TiO$_2$ patches, until they achieved the first Kerker’s condition, resulting in high transmission (i.e. strong forward scattering). After changing the polarization state of the incident light to the y-polarized wave, the first Kerker’s condition was no longer valid resulting in low backscattering. Further, owing to minimal absorption losses in the TiO$_2$, the proposed filter does not experience low damage threshold unlike commercially available film or metallic polarizers. The operating waveband (i.e. VIS-NIR-SWIR-MWIR) of the metasurface polarizer by modifying the geometrical parameters of the patches, and incorporation additional dielectrics such as Ge or Si.

![Figure 2](image)

**Figure 2:** The simulated transmission for the proposed polarizer shown in Fig. 1 for x- and y-polarized incident light.

### 3. Conclusions

In summary, we demonstrate a visible linear polarizer based on a TiO$_2$ metasurface which satisfies Kerker’s first condition. The polarizer exhibits a high extinction ratio (>2.8:1) and a low damage threshold. The concept can be extended to other wavebands by adjusting the geometrical parameters.
Abstract
Implementing dynamic tunability into the design of metasurfaces is one of the major challenges of the field today. In our contribution we will review various approaches to incorporation of vanadium dioxide into metasurfaces. In particular, we will explore utilization of VO$_2$ nanostructures as both Mie resonant and also propagation-phase building blocks of tunable metasurfaces.

1. Introduction
The key element of any metasurface are attributes of its building blocks (“meta-atoms”) – their constitutive materials, size, shape, and spatial arrangement. Originally, metasurfaces were assembled almost exclusively from metal nanostructures due to their strong plasmonic resonance and large scattering cross-section. The large intrinsic losses of the plasmonic resonators have been mitigated by use of dielectric nanostructures. Their strong Mie resonances based on displacement currents rather than ohmic currents lead to significantly reduced losses and gave rise to a novel class of dielectric metasurfaces. To have a significant industrial impact in high-volume applications like, e.g., mobile phone camera modules or wearable displays, the manufacturing process has to be further optimized for the existing foundry technology and, ideally, made tunable using mechanical, electrical, or optical control [1].

2. Discussion
Because the nature of plasmonic and Mie resonances strongly depends on the shape and mutual orientations of the individual meta-atoms, the primary approach how to incorporate tunability into metasurfaces is the one based on mechanical reconfigurability. The corresponding technological solutions involve mechanical deformations of the substrate or pure mechanical modifications in the realm of micro-electro-mechanical systems (MEMS). The second large class of tunable metasurfaces is based on modulation of charge-carrier density either in the substrate or in the meta-atoms themselves. The associated substantial change in the dielectric properties can be achieved through injection of free carriers into semiconductors like gallium arsenide or into conductive oxides like indium tin oxide. Another class of materials offering electro-optical tunability is the family of 2D materials, involving graphene and transition metal dichalcogenides. The third method how to achieve nanoscale optical and plasmonic switching is to employ materials that can undergo a radical phase change in the

atomic or electronic structure. A typical example of such materials are chalcogenide glasses, which can be repeatedly switched between their amorphous and crystalline states – in a process which is accompanied by a rapid change of their optical and electrical properties. This functionality allows storage of information, and it has been used for a long time in rewritable optical discs and phase-change memory devices [2]. What limits their practical applications are their high (~430 K) and broad (20–30 K) transition temperatures and a tendency to heat-induced degradation. The only other phase-change material with equivalent switching capability but without the limitations of chalcogenide glasses is vanadium dioxide (VO$_2$), which undergoes an insulator to metal transition (orders-of-magnitude large changes in resistivity) at 340 K, closest to the room temperature amongst natural materials exhibiting such transition. The low thermal hysteresis (5–10 K), possibility to induce the phase change also by electrical, optical, and strain stimuli, and millions of switching cycles without degradation all render VO$_2$ an attractive material for switchable or tunable metasurfaces.

There are basically two ways how can a phase-change material be incorporated into a metasurface. The more facile way is to employ it as a substrate with tunable properties and to fabricate the meta-atoms on top of it. Tunable perfect absorbers, tunable polarizing elements, and metamaterials with on-demand reflection and transmission resonances have been produced this way [3,4]. The more straightforward approach is the nanostructuring of the tunable material itself using some nanofabrication technique. Then, the resulting optical function of the metasurface can be controlled in a direct manner, while reducing the delays and inefficiencies caused by material heterogeneity [5-8].
3. Conclusion

In our contribution we will focus on the large potential represented by incorporation of VO$_2$ into tunable metasurfaces. Namely, we will discuss how one can utilize VO$_2$ nanostructures as direct building blocks of the dielectric metasurfaces in the visible range, taking advantage not only of their plasmonic state, but also of their low-loss Mie resonances (Figure 1) [9]. We will also discuss the limits of use of high aspect-ratio VO$_2$ building blocks in metasurfaces based on propagation phase and we will try to elucidate the complicated relationship between structural quality of the VO$_2$ and its optical properties in the visible range.

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References

Potential of pure VO$_2$ building blocks for tunable metasurfaces in the visible

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Abstract

Metasurfaces represent a new class of optical components, which can provide optical functions far beyond the current applications. Phase-change materials can upgrade them into tunable metasurfaces. Vanadium dioxide (VO$_2$) represents a volatile phase-change material, which can provide such tunability and which nanostructures were barely explored for metasurfaces in the visible. Here, we focus on the investigation of VO$_2$ nanocylinders in the visible. For that, we use FDTD simulations based on the refractive index obtained from our optimized VO$_2$ thin film.

1. Introduction

Encoding hologram information into various angular momentum of a photon or diffracting entangled photons to determine their prior polarization, functions that are hardly achieved with conventional optical components can nowadays accomplished with metasurfaces [1, 2]. Adding phase-change materials into metasurfaces can provide switching possibilities, where the metasurface is switched on and off [3], or it can encode information into various phases of such material, adding another degree of freedom [4]. One of the most promising material with the phase transition is VO$_2$. Its advantage lies in the volatile transition that occurs already around 67°C and the possibility to withstand millions of switching cycles without degradation [5]. One of the most promising material with the phase transition is VO$_2$. Its advantage lies in the volatile transition that occurs already around 67°C and the possibility to withstand millions of switching cycles without degradation [5]. Despite its absorbing nature, VO$_2$ exhibits large index modulation ($\Delta n \approx 0.5$) in the visible that significantly exceeds those of other phase-change materials [6]. Here, we present investigation of pure VO$_2$ metasurface building blocks that operate in the visible range. We carry out FDTD simulations that are based on the refractive index obtained from our optimized 200 nm VO$_2$ film, fabricated by electron beam evaporation and post-annealing.

2. Discussion

2.1. Thin film optimization

To examine the potential of VO$_2$ nanostructures for metasurfaces, we firstly obtained VO$_2$ refractive index from an optimized 200 nm thin film. The optimized film was deposited by evaporating stoichiometric VO$_2$ powder (Mateck) in an electron beam evaporator (Bestec, 8 kV, 32 mA, 1 Å s$^{-1}$) at room temperature, followed by 10 min of annealing at 450°C in a vacuum furnace under 15 sccm of O$_2$. The refractive indicies of low- and high-temperature phases of VO$_2$ were obtained by UV-NIR spectroscopic ellipsometer (J.A. Woollam, V-VASE). In Figure 1, we can observe almost equal absorption coefficients in both VO$_2$ phases over the whole visible range (marked by the grey background). Moreover, absorption of the low-temperature VO$_2$ phase in the near-infrared range decreases almost to zero, while the high-temperature phase exhibits very high-absorbing metallic character. Although modulation of the real part of the refractive index during the VO$_2$ transition is most pronounced between 1000 nm and 1500 nm wavelengths ($\Delta n_{NIR} \approx 1.3$), but in the visible it reaches still a reasonable contrast ($\Delta n_{VIS} \approx 0.7$). This makes VO$_2$ promising for tunable applications also in the visible.

2.2. Simulations

Using the refractive index from Figure 1, we simulated transmission phase and amplitude of pure VO$_2$ metasurface building blocks. First, finite ($5 \times 5$) arrays of nanocylinders were simulated using the finite-difference time-domain (FDTD) method implemented in the Lumerical FDTD Solutions software. Then, the far-field transmission phase
and amplitude response was calculated from currents of these nanostructures, using the Green’s function formalism [7]. Because dielectric Mie resonances in VO$_2$ nanostructures [4] and VO$_2$ non-zero absorption in the visible might significantly affect the blocks’ optical response, we investigated influence of different heights and spacings of nanocylinders on the transmission phase and amplitude. The first thing we observed was that the phase shift introduced by Mie resonances was suppressed by the absorption, resulting in a need for high-aspect ratio nanostructures. Nanocylinders with 500 nm height and 300 nm spacing, operating at 680 nm wavelength were most promising, as they exhibited 2$\pi$ phase coverage over an increasing diameter (Figure 2). However, because of the trade-off between the phase and absorption, the biggest nanocylinders exhibited only 10 % transmission. Higher nanocylinders resulted in larger phase, but lower transmission. The second thing we observed was almost equal transmission for both VO$_2$ phases, which resulted from very similar absorption coefficients (Figure 1). This similarity was disrupted for nanocylinders with larger spacing, as Mie resonances in low-temperature VO$_2$ phase got more pronounced. The third observation was almost $\pi$ phase modulation during the VO$_2$ transition for the largest nanocylinders in our study. Despite its absorbing nature, such high phase modulation in the visible was not reported to our knowledge and it paves the way for encoding information into various phases of VO$_2$ nanostructures.

3. Conclusions

Using the refractive index from the optimized VO$_2$ film, we have investigated pure VO$_2$ building blocks for propagation metasurfaces, operating in the visible. Despite the dielectric Mie resonances occurring in those nanostructures, the full-wave phase shift was reached only by high-aspect ratio nanostructures. The increased amount of material with absorbing nature of VO$_2$ resulted also in very low transmission ($\leq$ 10 %). This makes VO$_2$ lossy, but tunable dielectric material that might reach $\pi$ phase modulation during the transition.

Acknowledgement

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References

**Polarization-insensitive broadband achromatic metalens from ultraviolet to near-infrared regions**

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**Abstract**

Metalenses, consisting of a number of subwavelength nanostructures, have presented extraordinary abilities in compact and nanoscale optical devices. However, there still remains a challenge of achromatic aberration due to high phase dispersion of their building blocks, limiting the applications in multi-wavelengths or broadband ranges. To date, few works of broadband achromatic metalenses covering from ultraviolet (UV) to near-infrared regions have been reported. Here, we propose a simple polarization-insensitive metalens comprised of multi-layer metasurfaces to achieve an ultra-broadband achromatic focusing from ultraviolet to near-infrared regions. A wavelength-independent focal spot is observed at 355, 450 and 785 nm at a diffraction limit with focusing efficiencies of 12%, 30% and 58%. Our work provides a general approach in applications of various flat achromatic devices, such as full-color detection and imaging.

**1. Introduction**

Metasurfaces, referring to a two-dimension array of artificially engineered nanostructures, have shown extraordinary flexibility for manipulating wavefronts of electromagnetic waves due to their excellent properties in controlling the amplitude [1-3], phase [4-6] and polarization [7-9] of light. To date, there have been plenty of works on metasurface flat optics, such as beam deflectors [10-12], meta-holograms [13-15], metasurfaces [16-18] and waveplates [19,20]. As a vital part of flat optical devices, metalenses are widely used in spectroscopy [21,22], imaging [23-25], and virtual and augmented reality [26,27]. Compared with the conventional optical lenses, which utilize the curvature of the polished surface and the refraction of light to achieve the focusing, metalenses are able to focus the incident light through subwavelength nanostructures, which enable vast flexibility for significantly reducing the size of optical systems. However, achromatic aberration is still a big challenge in metalenses due to the resonant phase dispersion of nanostructures, the material intrinsic dispersion and the accumulation propagation phase difference between various wavelengths.

Achromatic aberration has been recently explored at several discrete wavelengths or in a relatively narrow bandwidth spectrum range through stacking multilayer metasurfaces or spatial arrangements. A multilayered metasurface with different materials and unit parameters at each sequential layer which is optimized for a specific wavelength is designed to achieve a triply red (650 nm), green (550 nm), and blue (450 nm) achromatic focusing [28]. Alternatively, diverse subwavelength nanostructures corresponding to a selected wavelength have been integrated into a single metasurface for achromatic aberration through spatial arrangements [29]. However, the focusing efficiencies are relatively low. Additionally, broadband achromatic metalenses have been recently reported in visible and near-infrared regions, through tailoring the phase profiles of nanostructures to compensate for phase differences between different wavelengths. A transmission broadband achromatic metalens consisting of GaN nanostructure units has been demonstrated in the visible region from 400 to 660 nm [30]. A reflection achromatic metalens comprised of coupled Au nanorods has been reported within a broad near-infrared bandwidth from 1200 to 1680 nm [31]. However, a single metalens composed of monolayer nanostructure is still insufficient for the compensation of the phase coverage to suppress the chromatic aberration in an ultra-broad bandwidth spectrum covering from ultraviolet to near-infrared regions.

Here, we demonstrate an ultra-broadband, polarization-independent metalens consisting of multi-layer metasurfaces to achieve an achromatic focusing from ultraviolet to near-infrared regions. The unit cell of the metalens is fabricated by hafnium oxide (HfO\(_2\)) nanopillar due to its low optical losses in the ultraviolet region, which has an UV-transparent window and relatively high refractive index [32]. A more than 2\(\pi\) phase coverage at all wavelengths is achieved in an ultra-broad bandwidth spectrum range due to the increasing phase accumulation from multi-layer nanostructures. The near-diffraction-limited focal spots are observed at wavelengths of 355, 450
and 785 nm with focusing efficiencies of 12%, 30% and 58%, respectively. Comparing with the chromatic metalens, the designed four-layer metalens shows a good achromatic aberration effect. Our work has highlighted a promising approach for realizing ultra-broad bandwidth optical applications from ultraviolet to near-infrared regions.

2. Results

2.1. Design principle

Figure 1a shows the schematic of a chromatic metalens (left) and an achromatic metalens (right), which are designed by monolayer and multi-layer metasurfaces, respectively. For chromatic metalens, the focal length is sensitive to the wavelength, which results from a phase dispersion of their nanostructures at each layer. And the achromatic metalens enables to focus the incident light into a same point at several discrete wavelengths or a broad bandwidth spectrum range. Figure 1b shows the relative phase distribution as a function of radial position with focal length $f$ at three different wavelengths ($\lambda_3 > \lambda_2 > \lambda_1$). The corresponding phase profile of a metalens can be calculated by [33]:

$$\phi_{\text{nano, theory}}(R, \lambda) = -\frac{2\pi}{\lambda} \left( \sqrt{R^2 + f^2} - f \right),$$

(1)

where $R$ represents the radial distance between an arbitrary point and the center of the metalens; $f$ is the focal length; and $\lambda$ is the light wavelength.

The unit cell of the metalens is based on a HfO$_2$ nanopillar embedded in a layer of polydimethylsiloxane (PDMS) on quartz substrate (the inset in Fig. 2a). The bandgap of HfO$_2$ is $E_g = 5.7$ eV, which is located at the deep-UV range and leads a negligible extinction coefficient at the ultraviolet region [32]. It is thus a good choice for optical devices working in the UV range. The height of the nanopillar is set to be 1000 nm, and the radius varies from 25 to 80 nm with a period of 200 nm. Figure 2a-c shows the transmission (black lines) and phase (red lines) of a HfO$_2$ nanopillar as a function of radius varying from 25 to 80 nm at wavelengths of 355 (Fig. 2a), 450 (Fig. 2b), and 785 nm (Fig. 2c). The transmissions of nanostructures are higher than $\sim$80% at three wavelengths. The phase of a nanopillar with the radius of 25 nm is $-0.32\pi$ at 785 nm, and it is $0.37\pi$ when the radius is 80 nm, as shown in Fig. 2c. The phase coverage between these two radii is calculated to be 0.69$\pi$. Strikingly, at wavelengths of 450 and 355 nm, the phase coverage can increase to 1.45$\pi$ and 2.22$\pi$, respectively. It is worth noting that the phase coverage at 450 and 785 nm is less than $2\pi$ (as shown in Fig. 2b,c). The HfO$_2$ nanopillar can be regarded as a truncated waveguide and the introduced phase of the nanostructure can be approximated as [33]:

$$\phi_{\text{nano}}(H, \lambda) = \frac{2\pi n_{\text{eff}}}{\lambda} H,$$

where $n_{\text{eff}}$ and $H$ represent the effective refractive index and the height of a nanopillar, respectively. According to equation (2), the introduced phase originating from a nanostructure decreases with the increasing wavelength. Therefore, the phase coverage decreases as the wavelength increases, which is consistent well with the simulation results (Fig. 2a-c). To achieve a phase coverage of more than $2\pi$, it is necessary to increase the height of the nanopillar. Therefore, more than three-layer nanopillars are essentially required to achieve a more than $2\pi$ phase coverage at 785 nm.

For a metalens composed of multi-layer nanostructures, the final phase and transmission are calculated by the sum of the phase and the product of the transmission of nanostructures at each layer. Remarkably, the radii of these nanostructures at each layer vary dependently, and an extra space is introduced to avoid the coupling between adjacent layers. The total phase $\phi_{\text{multi-layer, unit}}(r_1, \ldots, r_N, \lambda)$ and transmission $t_{\text{multi-layer, unit}}(r_1, \ldots, r_N, \lambda)$ of multi-layer units are given by:

$$\phi_{\text{multi-layer, unit}}(r_1, \ldots, r_N, \lambda) = \phi_{\text{eff}}(r_1, \lambda) + \phi_{\text{eff}}(r_2, \lambda) + \ldots + \phi_{\text{eff}}(r_N, \lambda)$$

$$t_{\text{multi-layer, unit}}(r_1, \ldots, r_N, \lambda) = \prod_{i=1}^{N} t_{\text{eff}}(r_i, \lambda)$$

(3)
Figure 2: (a-c) The simulated transmission (black lines) and phase (red lines) as a function of radius at wavelengths of 355 (a), 450 (b), and 785 nm (c). The unit cell consists of an amorphous HfO$_2$ nanopillar embedded in a PDMS layer on quartz substrate (inset). The period is $P = 200$ nm, the height is $H = 1000$ nm, and the radius $r$ varies from 25 to 80 nm. The phase (d-f) and transmission (g-i) for a unit cell composed of two-layer nanopillars as a function of radii $r_1$ and $r_2$ at wavelengths of 355 (d,g), 450 (e,h), and 785 nm (f,i).

The designed phase profile $\phi_{\text{design}}(R, \lambda)$ of the achromatic metalens is the sum of phase profiles of multi-layer metasurfaces, which is given by:

$$\phi_{\text{design}}(R, \lambda) = \sum_{n=1}^{N} \phi_{\text{metasurface}}(r_n, \lambda)$$

(5)

where $n \in [1, N]$, and $N$ is the layer number of multi-layer nanopillars; $r_n$ represents the radius of a nanopillar at $n^{th}$ layer. $\phi_{\text{metasurface}}(r_n, \lambda)$ is the phase distribution of $n^{th}$ layer metasurface at radial position $R$ and wavelength $\lambda$. According to equations (1) and (5), the phase deviation between the theoretical and designed phase can be described by:

$$\Delta \phi(R, \lambda) = \left| \phi_{\text{theory}}(R, \lambda) - \phi_{\text{design}}(R, \lambda) + 2\pi \right|$$

(6)

where $\phi_{\text{metasurface}}(r_n, \lambda)$ is the phase distribution of $n^{th}$ layer metasurface at radial position $R$ and wavelength $\lambda$.
Figure 3: (a-d) The theoretical (solid lines) and designed (asterisk symbols) spatial phase distributions of a metalens composed of monolayer (a), two-layer (b), three-layer (c), and four-layer metasurfaces (d) at wavelengths of 355 (black), 450 (orange), and 785 nm (blue). The diameter and focal length of the metalens are 10 and 12 μm, respectively.

where \( m \) is the integer. The designed phase is obtained when the phase deviation \( \Delta \phi(R, \lambda) \) meets the minimum at all radial position \( R \) and wavelengths \( \lambda \). All possible pairs of radii \( (r_1, r_2, ..., r_N) \) are selected to provide the phase combinations, achieving the required phase for an achromatic metalens. Figure 3a-d shows the theoretical (solid lines) and designed (asterisk symbols) phase of the achromatic metalens composed of monolayer (Fig. 3a), two-layer (Fig. 3b), three-layer (Fig. 3c), and four-layer (Fig. 3d) metasurfaces at wavelengths of 355 (black), 450 (orange), and 785 nm (blue). The diameter of the designed metalens is 10 μm, and the focal length is 12 μm. There is a significant optimization for the phase deviation as the layer number increases, and the designed phase matches well with the theoretical phase when the metalens is composed of four-layer metasurfaces, as shown in Fig. 3d.

2.2. Demonstration of achromatic metalens

Figure 4 shows the optical performances of an achromatic metalens which is composed of four-layer metasurfaces with a focal length of 12 μm. Figure 4a-c shows the intensity profiles along the propagation direction (z-axis) at wavelengths of 355 (Fig. 4a), 450 (Fig. 4b), and 785 nm (Fig. 4c). The simulated focal length is ~10.3 μm which is close to the theoretical value, and there is an obvious achromatic aberration compared with the chromatic metalens (Fig. S1). The slight difference of focal length between the simulation and theoretical prediction may be attributed to the phase deviation and wavefront divergence after the layer. Figure 4d-f shows the transverse intensity profiles across a given focal plane (the white lines in Fig. 4a-c). Normalized intensity profiles of the focal plane along the radial direction (x-axis) are plotted in Fig. 4g-i. The full-width at half-maximum (FWHM) of focal spots are 420, 530 and 980 nm at wavelengths of 355, 450 and 785 nm, respectively. It is very close to the diffraction limit of 418, 529 and 924 nm which are calculated by \( 0.514 \lambda / NA \), and shows nearly ideal optical performances. The focusing efficiencies, which is defined by the ratio of the optical power passing through a circular aperture with triple FWHM at the focal plane to the incident optical power, are 12%, 30% and 58% at 355, 450 and 785 nm wavelengths.

3. Discussion

The overall transmission of the multi-layer unit cell is the product of the transmission of nanopillars at each layer, resulting in a sharp decrease in focusing efficiency for low transmission nanostructures. At 355 nm wavelength, low transmissions of nanopillar structures (~80%, shown in Fig. 2a) result in a low focusing efficiency. The high focusing efficiency can be achieved by increasing the degree of freedom of structure parameters and optimizing the design method. Additionally, the achromatic metalens is polarization-insensitive due to the central symmetry of the
Figure 4: (a-c) Calculated axial intensity distributions in the x–z plane at wavelengths of 355 (a), 450 (b), and 785 nm (c). (d-f) Calculated intensity profiles at the focal plane (white dashed lines in a–c) at wavelengths of 355 (d), 450 (e), and 785 nm (f). (g-i) Normalized intensity profiles as a function of radial position with full-width at half-maximum of 420, 530 and 980 nm, respectively.

nanostructure, indicating the identical focal performances under various incident polarized light (Fig. S2).

4. Conclusions

In summary, we have proposed a polarization-insensitive ultra-broadband achromatic metalens from ultraviolet to near-infrared regions based on multi-layer metasurfaces. The low optical loss dielectric material, HfO$_2$, in the ultraviolet region is used to fabricate the nanopillar, and four-layer nanopillars are applied to achieve more than 2π phase coverage in an ultra-broad spectrum range. The focal length of our achromatic metalens remains almost unchanged as the incident wavelength varies from ultraviolet (355 nm) to near-infrared (785 nm) regions, verifying an apparent elimination of chromatic aberration. The near-diffraction-limited optical performances have been demonstrated with the focusing efficiencies of 12%, 30% and 58% at wavelengths of 355, 450 and 785 nm, respectively. Moreover, the spectrum bandwidth and optical performances of the achromatic metalens can be further improved by increasing the degree of freedom of structure parameters and optimizing the design method. Our work provides a promising application for flat broadband optical devices.

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References


Beam-type Elastic Metagratings for Selective Reflections of Longitudinal Waves

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Abstract
Metagratings have recently received much attention in electromagnetic and acoustic wave research fields. Governed by the diffraction grating theory, metagratings enable precise wavefront steering by suppressing undesired high-order scattering modes. Recently, we proposed a novel elastic metagrating model using a periodic arrangement of beam-type members in order to realize efficient steering of longitudinal waves [1]. Based on analytical modeling of the beam-type elastic metagratings, anomalous reflections and asymmetric splitting of longitudinal waves were realized successfully in numerical and experimental studies.

1. Introduction
The diffraction grating theory has been expanded to realize anomalous wave steering for electromagnetic and acoustic waves [2,3]. The periodic structures, so-called metagratings, along the boundary of the continuum are designed to suppress superfluous propagations of high-order scattering modes, such that the metagratings allow the accurate steering of wavefront in a selective manner. In elastic metagrating research, however, a few studies managing diffraction modes by solving inverse problems was reported to search for appropriate geometric parameters of the scatterers [4].

In the circumstance, we proposed a novel elastic metagrating to realize anomalous wave steering of longitudinal elastic waves [1]. The elastic metagratings are composed of slender and straight beam-type members to steer the reflection of longitudinal elastic waves in an efficient manner. To find out the geometric values of the beam-type members realizing anomalous reflections and asymmetric splitting, a gradient-based optimization algorithm was employed. The results showed that the phase modulation is the key physical phenomena for the selective reflections of the longitudinal waves from the designed metagratings. It is expected that the present beam-type elastic metagrating model can be applied for non-destructive structural health monitoring and medical imaging in the near future.

2. Description of the elastic wave motions in the beam-type metagratings
Fig. 1 shows a schematic configuration of the beam-type elastic metagratings [1]. In the illustration, in-plane incident longitudinal wave and several scattered longitudinal waves are presented together. The grating equations for longitudinal and shear waves, respectively, are given by:

\[ k_p^s = k_p \sin \theta_{p,ref} = k_p \sin \theta_{p,inc} + \frac{2\pi n}{a} \]  
\[ k_s^s = k_s \sin \theta_{s,ref} = k_s \sin \theta_{s,inc} + \frac{2\pi n}{a} \]

where symbols \( k \) and \( \theta \) are the wave number and the angle of wave propagation. The subscripts \( p \) and \( s \) denote the longitudinal and shear elastic waves, respectively. \( n \) and \( a \) are the diffraction mode number and the periodicity of the unit cell. And the subscripts \( inc \) and \( ref \) indicate the incident and reflected waves, respectively.

The unit cell of metagratings consists of slender and straight beam-type member arrays. Each beam-type member is modelled to describe longitudinal and flexural motions, such that the wave fields between the elastic continuum plate and the beam-type members are fully coupled along the interfaces.

![Figure 1: A schematic illustration of the beam-type elastic metagratings for selective reflections of longitudinal waves [1].](image)
3. Realization of selective reflection of longitudinal wave

As examples of selective reflections of longitudinal waves, anomalous reflections and asymmetric splitting were realized using the beam-type elastic metagratings [1]. The periodicity of the unit cell is calculated from Eq. (1) and the geometric parameters such as lengths of each beam-type member are searched using a gradient-based optimization algorithm. Fig. 2 shows the result of anomalous reflection for normally incident longitudinal wave. The target reflection angle is selected to be $45^\circ$.

![Figure 2: The anomalous reflection with the target reflection angle of $\theta_{\text{t}} = 45^\circ$ using the designed beam-type metagrating ($\theta_{\text{t}} = 45^\circ$) [1].](image)

4. Interpretations and verifications

To understand the physical characteristics and the length variations of the beam-type members, we consider the unit cell of the present metagratings as a super cell consisting of multiple subcells. For example, the unit cell in Fig. 2 can be considered as six divided subcells as shown in Fig. 3.

![Figure 3: The reflected longitudinal wave fields of six subcells and the corresponding phase profiles over the subcells [1].](image)

As shown in Fig. 2 the beam-type members have similar lengths around the resonating dimensions, each of which causes a significant phase shift at the resonance frequency. The phase profiles in Fig. 3 show that the accumulated phase shifts produced by the six subcells cover a $2\pi$ span over the unit cell of the metagrating. Such a phase modulation is the main physical phenomenon to realize the anomalous reflection of longitudinal wave in the present metagratings.

As experimental verification, the periodic metagrating array in an aluminum plate is manufactured [1]. The experimental results matched well with the numerical predictions for the selective reflection with the angle of $45^\circ$ as shown in Fig. 4.

![Figure 4: The experimental setup of the designed elastic metagrating array and the comparison of the experimental data with numerical ones [1].](image)

5. Conclusions

The recently proposed beam-type elastic metagratings are successfully realize selective reflections of longitudinal waves by suppressing undesired high-order scattering modes. The beam-type members are so useful to represent the longitudinal and flexural wave motions that the dynamic responses between the elastic continuum plate and beam-type members can be analytically coupled along the interfaces. The phenomena of anomalous wave steering are both physically interpreted using phase modulation and experimentally verified. We expect our proposed elastic metagratings can pave the way for practical applications, such as non-destructive structural health monitoring and medical imaging.

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References


Influence of the Number of Cells for Finite Size Artificial Magnetic Conductor

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Abstract
This paper examines the influence of the cell number for finite size AMC under normal plane wave incidence. A comparison is carried out on the operational frequency, the fractional bandwidth, and the reflection coefficient magnitude between the finite size AMC and an infinite structure, for different cell numbers and for three different finite size screens.

1. Introduction
Artificial Magnetic Conductors (AMC) are usually characterized with infinite boundary conditions and under normal plane wave incidence. Their operational frequency is defined when the reflection phase is 0°. This in-phase reflection property has made possible the design of low-profile antenna [1]-[4]. The effect of the AMC size has been examined for a finite square structure compared to the infinite unit cell response [5], for various unit cells configurations [2], and for low-profile antennas with a dipole over an AMC by varying the total surface of the screen [1]-[3]. However, the choice of the number of cells for a given surface has not been studied in details to the best of our knowledge and various configurations were suggested for the smallest square AMC studied: 2 x 2 [4], 4 x 4 [5], 5 x 5 [2, 3], and 6 x 6 [1] unit cells.

In this paper, the influence of the cell number for a finite size AMC under normal plane wave incidence is investigated. The unit cell is a metallic square patch over a grounded substrate. For a given surface, the number of cells is increased and the size of the unit cell is reduced, but the operational frequency remains the same by tuning the capacitor value placed in series between each patch. Operational frequency, fractional bandwidth and reflection coefficient magnitude (Γ) are compared between the finite size AMC and the infinite structure, for different numbers of cells (N x N cells, 2<N<32) and for three different finite size screens (0.45λ₀ x 0.45λ₀, 0.63λ₀ x 0.63λ₀, 0.77λ₀ x 0.77λ₀).

2. Reference unit cell and finite AMC structures
The unit cell is a metallic square patch over a grounded FR4 substrate (εᵣ = 4.4, tanδ = 0.02), which height is h = 19.9 mm (λ₀/42). The gap between each patch is g = 2.5 mm (λ₀/333) and is kept constant regardless the number of cells. A lumped capacitor is placed in series between each patch edge and its value allows to tune the operating frequency while the size of the square patch is reduced. With infinite boundary conditions and under normal plane wave incidence, each unit cell is tailored to operate at 360 MHz (λ₀ = 833.33 mm). Three AMC sizes are considered. Their dimensions and simulated cell configurations are summarized in Table 1. Table 2 details the cell configuration, for different numbers of cells on surface S1 (0.45λ₀ x 0.45λ₀).

Table 1: Examined AMC structures.

<table>
<thead>
<tr>
<th>Surface</th>
<th>Size [λ₀λ₀]</th>
<th>Configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.45 x 0.45</td>
<td>3 x 3 to 24 x 24</td>
</tr>
<tr>
<td>S2</td>
<td>0.63 x 0.63</td>
<td>4 x 4 to 32 x 32</td>
</tr>
<tr>
<td>S3</td>
<td>0.77 x 0.77</td>
<td>5 x 5 to 30 x 30</td>
</tr>
</tbody>
</table>

Table 2: Unit cell dimension and capacitor value for surface S1.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Patch edge size [mm]</th>
<th>Periodicity [mm]</th>
<th>Capacitor value [pF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 x 3</td>
<td>125.00</td>
<td>127.50</td>
<td>0</td>
</tr>
<tr>
<td>6 x 6</td>
<td>(λ₀/6.7)</td>
<td>(λ₀/6.5)</td>
<td>3.11</td>
</tr>
<tr>
<td>10 x 10</td>
<td>33.25</td>
<td>35.75</td>
<td>5.03</td>
</tr>
<tr>
<td>18 x 18</td>
<td>18.75</td>
<td>21.25</td>
<td>6.65</td>
</tr>
</tbody>
</table>

3. AMC properties and RCS
The AMC properties for finite size structures are retrieved from monostatic Radar Cross Section (RCS) method, under normal plane wave incidence. The reflection coefficient is related to the reflection coefficient through the equation (1) [6]:

\[ Γ = 20 \log \left( \frac{σ_{AMC}}{σ_{ref}} \right) \]  

where Γ is the reflection coefficient in dB, σ_{AMC} is the RCS of the AMC in m², σ_{ref} is the RCS of the reference object in m². The reference plane considered here is a copper located at height h, and its size depends on the AMC under study (S1, S2 or S3). The AMC bandwidth is defined as the frequency bandwidth where the reflection phase is in the range ±90°.
4. Simulated results

As the surface of the AMC increases, the operating frequency of the finite AMC tends to decrease towards the frequency of the unit cell in infinite configuration: around 392 MHz for S1, 385 MHz for S2 and 375 MHz for S3, Figure 1. The operating frequency of the finite AMC is shifted to the highest frequency, as in [5]. As the surface is reduced, the operating frequency converges more quickly to its limit value, with less dense configurations: 12 x 12 cells for S3, 8 x 8 cells for S2 and 4 x 4 cells for S1. Increasing the number of cells does not enable the operating frequency to get closer to the tailored frequency. The fractional bandwidth of the finite AMC tends to increase towards the fractional bandwidth of the unit cell in infinite configuration as the AMC size increases, Figure 2. For the surfaces S2 and S3, the simulated results show that the bandwidth can be slightly better than the infinite case when the cells configuration is high, from 12 x 12 for S3 and from 20 x 20 for S2. The reflection coefficient magnitude indicates indirectly the level of energy absorbed by the AMC, Figure 3. The simulated results show that the finiteness of the AMC leads to lower reflection coefficient magnitude compared to the infinite unit cell configuration. As the number of cells increases for a given surface, the reflection coefficient magnitude increases, improving the AMC performances. For the finite AMC S2 and S3, the reflection level ceases to increase regarding the number of cells from 12 x 12 cells configuration. In the case of the surface S1, the curve tends on average to the maximum value of the reflection coefficient from 20 x 20 cells.

5. Conclusions

The number of cells and the size of an AMC have an influence on the operating frequency, the fractional bandwidth and the reflection coefficient magnitude of the AMC. As the surface of the AMC may be constrained by size requirements, the number of cells can be considered as a parameter to modify the performance of the AMC. A small number of cells induces a lower reflection coefficient magnitude, therefore higher energy absorbed by the AMC, and a lower bandwidth compared to the infinite cells structure. A higher number of cells enables to get closer to and even to exceed the bandwidth of the infinite cells case, depending on the size of the AMC. However, within the framework of reconfigurable metasurface by means of tunable capacitors, increasing the number of cells leads to enhance the complexity of the metasurface and its control circuitry.

References


Nonlinear metamaterials
All-Optical Switching of an Epsilon-Near-Zero Plasmon in ITO

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Abstract

A new class of materials with a vanishing permittivity, known as epsilon-near-zero (ENZ) materials, has been reported to exhibit unprecedented ultrafast nonlinear efficiencies within subwavelength propagation lengths. We study the pump dependent near perfect absorption ENZ plasmon in a thin indium tin oxide (ITO) layer. Utilising the Kretschmann configuration combined with the ENZ plasmon resonance could pave the way towards ultrafast switching from near-perfect absorption to total internal reflection or vice versa.

1. Introduction

With the rise of new computational demands such as artificial intelligence chips, all-optical signal processing is often seen as a breakthrough technologies for the next generation of computation and communication devices [1]. However, the desire to enable all-optical signal processing is limited by most materials only providing an extremely weak optical nonlinearity. Hence, larger energy consumption and size of the devices are necessary to compensate the weak response of the materials used so far, making integration into existing nanophotonic platforms challenging [2]. For easy implementation into existing platforms the materials should be compatible with existing complementary metal–oxide–semiconductor (CMOS) fabrication technologies [3].

Recently, epsilon-near-zero (ENZ) materials got much attention, not only for their intriguing linear properties [4], but also more recently for their large optical nonlinearity [2]. For applications in the telecom wavelength range so called transparent conductive oxides have proven to be a good material choice. The variability their doping level during fabrication gives control over the ENZ wavelength position spanning the infrared (IR) wavelength range. Indium-tin-oxide (ITO) as one example showed to undergo a refractive index change of the order of unity upon illumination with light at an angled incidence [5]. Similar effects have been measured for materials such as AZO [6] or CdO [7].

To further increase this large nonlinearity, different strategies have been employed. To reach larger and more broadband changes in refractive index a thin layer of ITO was covered with gold antennas [8]. A cavity based on CdO and gold was used to achieve a nearly perfect absorbing Berreman mode which is utilised for femtosecond polarization switching, however, working at a wavelength around 2.1 µm [7].

However, these solutions either require nano-structuring or the additional support of a cavity. To avoid that, another study used the Kretschmann configuration to efficiently generate third harmonic radiation [9]. The ENZ mode of a thin ITO layer was excited leading to an enhancement of the incoming field. This ENZ plasmon also provides near-perfect absorption (PA) at a designable wavelength in the NIR [10].

Here, we show the nonlinear shift of this ENZ plasmon via pump-probe experiments in the Kretschmann configuration. The design provides a potential platform to switch from near-total absorption to total internal reflection upon tuning the plasmon resonance into and out of the probes spectral range, while utilizing the efficient near perfect pump absorption through the ENZ plasmon. Furthermore, the design doesn’t require the building of an additional cavity or micro structuring, as it only requires a single 60 nm layer of ITO on a substrate.

2. Measurements

The NIR permittivity of the 60 nm ITO film was measured in an ellipsometer and can be described by the Drude model,

$$\varepsilon_{\text{ITO}}(\omega) = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + i\omega\gamma},$$

(1)

with $\varepsilon_{\infty} = 3.43$ as the high-frequency permittivity, $\omega_p = 2.86 \times 10^{15}$ as the bulk plasmon frequency and $\gamma = 2.24 \times 10^{14}$ as the damping rate. Recent measurements have shown that pumping below the band-gap of the TCO material leads to carrier heating which subsequently results in an increased effective mass and a decreased plasmon frequency $\omega_p$ [5].

This shift also directly influences the near perfect absorption ENZ plasmon resonance, which we measure in a Kretschmann configuration pump-probe setup as seen in Fig. 1. Due to the prism, beams can approach the ITO layer beyond critical angle and thereby excite the plasmon resonance. The probe is chopped and a total internal reflection...
Figure 1: Schematic pump-probe setup with 60nm ITO layer on a prism to excite the ENZ plasmon beyond the critical angle.

Figure 2: Angle and Frequency resolved reflection for the initial case (top) and pumped case (bottom), corresponding to a 75 GW/cm² peak intensity pump. The expected plasmon dispersion is red dashed.

The experimental results show a pronounced shift of the plasmon resonance by $\sim 20$ THz. This leads to absolute differential reflection changes ($\Delta R$) beyond 50 % and relative differential reflection changes ($\Delta R/R_0$) beyond 1000 % (starting with $\sim 98$ % absorption) or up to $\sim 100$ % (ending on shifted resonance). Fig. 2 also shows that the shifting behaviour agrees with transfer matrix model predictions based on previous optical refractive index studies of ITO [5]. The calculated mode dispersion is red dashed and confirms the ENZ plasmon, which corresponds to the back-bended transition area of the dispersion between volume- and surface-plasmon character.

In conclusion, we show all optical switching of an non-radiative epsilon-near-zero plasmon. Tuning from near perfect absorption to total internal reflection, limited by the losses of the TCO layer, could pave the way towards all optical (plasmon) switching at telecom frequencies. Materials with higher mobility and lower losses such as CdO for longer IR wavelength would even further improve the differential reflection and reduce the required pump fluency. The compatibility with CMOS fabrication technique makes thin ITO layers offers a compelling new route for nonlinear integrated photonics applications.

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References


Thermally tunable invisibility at terahertz: different mechanisms in one structure

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Abstract
Thermally tunable invisibility at terahertz frequencies is revisited with the focus on the contribution of different mechanisms achievable in different frequency and permittivity ranges. The mechanisms based on localized surface plasmon resonances and volume-mode resonances in high-index dielectric shells and others may co-exist for one scatter, enabling on-off switchable functionality.

1. Introduction
Invisibility and cloaking represent examples of ultimate control of electromagnetic wave scattering. Indeed, a scatter can vanish for a far-field observer, in spite of having such an electrical size and material properties that significant scattering may be expected. Several mechanisms of invisibility have been proposed to the time for 2D structures (mainly, single core-shell cylinder scatters), which include the ones based on transformation optics [1], scattering cancellation [2], interferences [3], and localized surface plasmon resonances [4]. Control of scattering has also been investigated in case of 3D scatters [5,6]. Merging the ideas of scattering control with the capabilities of dynamically tunable materials may yield new physical scenarios and functionalities. In this work, the thermally tunable invisibility at terahertz frequencies, which has initially been introduced in [7], is revisited with the focus on different mechanisms that are possible in different frequency and permittivity ranges.

2. Materials
Materials with dynamically controllable transition from the plasmonic state to the insulator state have attracted a lot of attention in the last decade. Graphene, ITO, and VO2 are probably the best known among these materials. From the scattering control perspective, they are interesting because the both states can be achieved when frequency is fixed, so that switching between visibility (strong scattering) and invisibility (very weak scattering) is possible. Two materials, InSb and VO2, have been assessed. The lack of the usable data on the continuous variation of VO2 permittivity with temperature at given frequency led to the fact that the focus was put on the structures made of InSb, for which such data are available [8].

Figure 1 presents examples of the frequency dependence of InSb permittivity in the terahertz range. Transition from the plasmonic state to the insulator state can be obtained while decreasing temperature, T. The larger the frequency, the smaller is the difference in permittivity corresponding to two fixed values of T. However, if a larger permittivity is needed, a larger frequency should be taken.

3. Results and Discussion
We consider scattering on single coated-cylinder (core-shell) scatters and arrays on their basis. A dielectric core cylinder of permittivity $\varepsilon_c$ is assumed to be coated with a shell made of a thermally tunable material of permittivity $\varepsilon_s$ (see inset in Fig. 1). The structure is illuminated by a plane electromagnetic wave. Figure 2 presents examples of the normalized scattering cross section as a function of frequency. Up to three bands with suppressed scattering cross-section are observed in the considered frequency range. Variations in temperature allow us to control spectral location of the scattering suppression regimes. An ultimate switching between strong and (very) weak scattering takes place while decreasing T from 345 K and 295 K, as observed in Fig. 2(a) at $ka=1.72$, in Fig. 2(b) at $ka=1.68$, and in Fig. 2(c) near $ka=0.8$ ($k=\omega/c$). The inverse switching scenario can be obtained when a stronger scattering is obtained at $T=295$ K, as occurs near $ka=1.2$, see Figs. 2(a)-2(d). These and other regimes are possible due to coexistence of the resonances having different nature and non-resonant effects, which appear at different frequency bands.
in one structure. Indeed, $\text{Re} \varepsilon_c$ is varied in a very wide range that enables such different phenomena.

![Figure 2: Scattering cross section for (a) $b/a=0.43$ and $\varepsilon_c=2.5$, (b) $b/a=0.43$ and $\varepsilon_c=4.5$, (c) $b/a=0.71$ and $\varepsilon_c=2.5$, (d) $b/a=0.71$ and $\varepsilon_c=4.5$; TE polarization. Normalized frequency is shown in units of $ka$.](image)

Figure 3: Magnetic (axial) field distribution for three different regimes of scattering suppression; left panel – $ka=0.59$, middle panel – $ka=0.74$, right panel – $ka=1.68$; $b/a=0.43$, $\varepsilon_c=4.5$, $T=295$ K, TE polarization.

Figure 2 presents magnetic field distribution at three weak-scattering minima that occur at $T=295$ K in Fig. 2(b). In the left, middle, and right plot, we have $\text{Re} \varepsilon_c=-7.47$, $\text{Re} \varepsilon_c=0.85$, and $\text{Re} \varepsilon_c=12.8$, respectively. These values are consistent with the expected nature of the scattering suppression mechanisms, which may include (but not restricted to) the ones based on the localized surface plasmon resonances [4] and the volume-mode resonances in high-index dielectric shells [3,7]. It is noteworthy that some of the weak-scattering regimes can be insensitive to the utilized variation of $T$, as observed in Fig. 2(d) at $ka=0.73$. In this case, a localized surface plasmon resonance at $T=345$ K spectrally coincides with a low-positive-permittivity regime of InSb at $T=295$ K (see the middle plot in Fig. 3).

The results obtained for the single scatters were used as entry point for the study of the arrays composed of the dielectric and metallic cylinders coated with InSb shells. The 2D arrays being similar, in terms of geometry, to the ones in [9] have been studied, and the effects originating from the properties of a single scatter and the ones occurring as a result of periodic arrangement of the individual scatters have been distinguished. Finally, 3D arrays of finite-length core-shell cylinders were examined.

The specifics of VO$_2$ as an alternative shell material has been evaluated for both single scatters and arrays on their basis. Whereas the material properties of VO$_2$ at terahertz frequencies can be suitable to achieve invisibility, the lack of the well justified data on the temperature dependence of permittivity is a big disadvantage. Once such data will be available, the main properties detected for the structures with InSb shells should be revisited for the structures with VO$_2$ shells. Generally, the latter is considered as a more prospective material than the former. However, a lower value of max$\text{Re} \varepsilon_c$ may make VO$_2$ less suitable due to a weaker potential in the high index related mechanism of scattering suppression, which is especially important while working at $a=\lambda/4$ ($\lambda$ is free-space wavelength).

4. **Conclusions**

The obtained results show that InSb and (to a smaller extent) VO$_2$ are appropriate materials to obtain different mechanisms of invisibility at terahertz frequencies. Temperature variations may enable a significant change in spectral locations of invisibility regimes for a single core-shell scatter. In addition, the specifics of the arrays composed of such periodically located scatters have been investigated. A comparative study of different geometries and tunable materials will be conducted at the next step of this research program.

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**References**


Negative refraction in time-varying, strongly-coupled plasmonic antenna-ENZ systems

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Abstract

We demonstrate high efficiency in the generation of optical induced time-reversal phase conjugate and negative refraction waves, from a temporal modulated deeply subwavelength epsilon-near-zero (ENZ) film integrated within a plasmonic metasurface. The strong coupling between the plasmonic resonance and the ENZ modes leads to a conversion efficiency that is more than 4 orders of magnitude greater than the bare ENZ film.

1. Introduction

Metasurfaces based on active materials, wherein the refractive indices can be modulated in time by an optical perturbation, allows a fast control of their electromagnetic properties while maintaining the subwavelength size [1]. Recent achievements using homogeneous epsilon-near-zero (ENZ) media, such as Indium tin oxide (ITO) and Aluminum-doped zinc oxide (AZO), have attracted attention due to the order-of-unity refractive index change which can be optically induced in such materials [2]. This makes it possible to achieve efficient temporal modulation uniformly across the medium, resulting in optically induced negative refraction with unity efficiency [3, 4].

Recently, an appealing room-temperature strongly coupling system based on plasmonic resonators on top of deeply sub-wavelength ENZ films has been observed [5]. Here, the fundamental plasmonic resonance of the metal resonator is coupled with optical modes supported by the ENZ thin film at frequencies where the real part of the dielectric permittivity crosses zero, which are called the ENZ modes. Their interaction leads to a strongly coupled system where the optical energy density is enhanced within the ENZ layer. This strong light-matter interaction in such metamaterials allows a dramatic reduction of the required optical intensity for the refractive index change [6].

In this work, we propose a time-varying metasurface, based on gold nanoantennas on a 40-nm-thick ITO film, as a suitable platform to generate optically induced time-reversal Phase conjugate (PC) and Negative refracted (NR) signals with less than 1 GW/cm\textsuperscript{2} of optical pump intensity.

2. Results

We perform a degenerate four-wave-mixing (FWM) where both the incident beams have the same wavelength. The schematic in Fig. 1a shows the NR and PC generation from the time-varying metasurface. The optical pump beam has normal incidence on the sample, while the probe is incident at a small (6 \textdegree) angle. The two laser pulses are co-polarized (parallel to the long axis of the antenna) and have a temporal duration of 240 fs, and 100 kHz repetition rate. The generated NR and PC are measured with a photodiode and com-

Figure 1: (a) Schematic representation of PC and NR generation form the strongly coupled plasmonic-antenna-ENZ system. (b) Measured transmission spectra of the metasurface at normal incidence.
In Fig. 2a we show the measured efficiency \( \eta \) of PC and NR for an optical pump intensity of 2 \( \text{GW/cm}^2 \) as a function of wavelength when pump and probe are overlapped in time. The absolute efficiency of the two nonlinear processes is almost 100\% for the strongly coupled system. The FWM efficiency of the bare ITO film is multiplied by 1000 (dashed black curve). (b) Numerical calculation (red) and measured (blue dashed-dot line) enhancement factor \( \eta_{\text{norm}} \) for the same metasurface with an optical pump intensity of 0.5 \( \text{GW/cm}^2 \).

In the strongly coupled system, the optical energy density within the nonlinear medium is enhanced by a factor greater than 40. This is explained by the fact that in the strongly coupled system the optical energy density with respect to the bare ITO. The reported efficiency generation obtained with a relatively low optical pump intensity, results to be 15000 times greater with respect to the case of the bare ITO. Following the recent discoveries regarding the nonlinear response of ENZ media, such efficient time-dependent metasurfaces could provide a route towards applications at the nanoscale that rely on light-with-light modulation ensuring a reduced operating power while maintaining high efficiency.

3. Conclusions

A time-varying strongly coupled plasmonic-antenna-ENZ system has been explored in order to produce time-reversal PC and NR fields. Due to the optical energy density enhancement within the nonlinear medium in the strong coupling regime, the efficiency generation of the nonlinear processes, obtained with a relatively low optical pump intensity, results to be 15000 times greater with respect to the case of the bare ITO. Following the recent discoveries regarding the nonlinear response of ENZ media, such efficient time-dependent metasurfaces could provide a route towards applications at the nanoscale that rely on light-with-light modulation ensuring a reduced operating power while maintaining high efficiency.

References


Plasmonic Enhancement of Second-Harmonic Generation with Film-Coupled Nanopatch Antennas

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Abstract

Field enhancements associated with resonant excitation of plasmonic structures have shown tremendous potential to improve the efficiencies of nonlinear wave-mixing processes at the nano-scale. In this work, we present an optimal mode-matched second-harmonic generation from hybrid-plasmonic film-coupled nanopatch antennas.

1. Introduction

Optical frequency conversion offers opportunities to achieve nanophotonic devices for applications in telecommunications, metrology and optical spectroscopy \(^1\). Conventionally, higher incident intensities and micrometer-scale interactions (phase-matching) are necessary conditions for efficient frequency conversion \(^2\). However, such conditions are difficult to fulfill on a nanometric scale. Nevertheless, efficient nonlinear interaction at small scales is desirable to realize integrated optical devices. To this end, nano-systems of dielectric \(^3\), metallic \(^3\), or hybrid-plasmonic (metallic/dielectric) \(^4\) nano-systems have been exploited. To boost nonlinear interactions, most systems utilize field enhancement of surface plasmon resonances (SPRs), while phase-matching conditions are often relaxed due to the device’s small footprints. In general, however, for efficient frequency conversion in a nano-system requires, one should fulfill all the following conditions at once: excitation of resonant modes at all the frequencies involved in nonlinear process, significant spatial overlap between the modes, and efficient coupling of near-field to the far-field \(^4\).

Plasmonic film-coupled nanopatch antennas are advantageous as they offer a controllable way to generate plasmonic resonances in the visible and near-infrared spectrum \(^5\). Such system forms a “plasmonic-junction” (the gap between metallic patch and the film), which provides large intensities and field confinements as well as a way to incorporate a wide variety of nonlinear optical materials. Moreover, the optimization of design parameters and selection of incident polarization enable the excitation of various higher order modes in distinct wavelength ranges. In frequency conversion, these modes can be utilized to match the frequencies involved in the process. The conditions of spatial overlap between the interacting modes can be satisfied by selecting modes with the right symmetry. Efficient free-space emission of the generated signal is further guaranteed by nano-patch’s magnetic-dipole-like emission \(^5\).

Here, we present numerical investigation of second-harmonic generation (SHG) by film-coupled nanopatch antennas \(^6\). We studied two mode-matched SHG configurations of distinct modal interactions. We discuss how linear modal structure of the interacting modes in each of the configuration affect the corresponding SHG efficiencies. The source of nonlinearity considered in the study is a non-centrosymmetric dielectric material embedded in the gap between the patch and the film (a hybrid-plasmonic configuration).

2. Results and Discussion

By independently modifying the width “A” and depth “B” of the patch (see \(^1\)), it is possible to match the fundamental field (FF) and second-harmonic (SH) to the first- and second-order (SHa) or third-order (SHb) Fabry-Perot modes of the gap-plasmon. Fig. \(^1\) shows the linear reflectance spectra of the system for a TM-polarized plane wave, under normal and oblique illuminations.

In the following, we consider two designs of film-coupled nanopatch antennas optimized for SHG. In the first design we tune the mode-FF and mode-SHb at the fundamental and second-harmonic wavelength respectively, for an infrared to visible conversion. In the second case we consider the interaction of mode-FF with the mode-SHa for an infrared to infrared conversion. We extracted SHG efficiency spectra for both the configurations as a function of the incident angle and FF’s wavelength \(^6\), for input intensity of \(I_{FF} = 55\text{MW/cm}^2\). For the interaction of mode-FF and mode-SHb, we attain SHG efficiency of the order of \(1.2 \times 10^{-9}\), under normal illuminations, which peaks with a value of \(2.4 \times 10^{-9}\) at incident angle of \(\theta \approx 45^\circ\). The origin of this behaviour can be associated to the maximization of overlap integral. The overlap integral represents a measure
of the energy transfer from the FF to the SH, defined as:

$$I_{ov} \propto \int \chi^{(2)} \cdot E_{FF}^* E_{SH}^* dv$$  \hspace{1cm} (1)

In Eq. 1, $E_{FF}$ and $E_{SH}$ is the linear local field at the fundamental and second-harmonic frequency, respectively, and $\chi^{(2)}$ is the nonlinear susceptibility tensor. The overlap integral for interaction of mode-FF and mode-SHb, under normal illuminations, is minimized due to anti-symmetric nature of mode-SHb (see Fig. 1(e)), resulting in a smaller conversion efficiency. For oblique illumination of the FF field, however, a break in the symmetry results in increase of overlap integral, leading to higher SHG efficiency [6].

Similarly, for the interaction of mode-FF and mode-SHa, we attain minimum efficiency of the order of $\approx 10^{-12}$, under normal illuminations, as mode-SHa cannot be excited. For oblique illumination, the system exhibits gradual increase in the SHG with maximum values of $5.5 \times 10^{-6}$ at $\theta \approx 35^\circ$. The maximum SHG efficiency in this system is increased twofold in comparison with the peak efficiency of the previous design.

Both the studied configurations demonstrated maximum possible SHG efficiencies under oblique illuminations. However, we demonstrated in [6] that this inconvenience can be circumvented by the loading of a periodically-poled Ferroelectric spacers and aligning the system such that the $\chi^{(2)}$ sign switches at the center of the patch. With such design, we observed SHG efficiency of the order of $2.0 \times 10^{-6}$ for the interaction of mode-FF and mode-SHb, under normal illumination. This increase is attributed to break of the symmetry due to change in the sign of the $\chi^{(2)}$, which consequently optimizes the overlap integral [6].

3. Conclusions

We have numerically investigated SHG from plasmonic film-coupled nanopatch antennas, for distinct mode-matched configurations. On the basis of their extracted SHG efficiency spectra, we conclude that the better spatial overlap of the interacting modes attribute to an enhanced SHG. We further proposed a novel configuration to attain favourable excitation conditions, without compromising the SHG efficiency [6]. The SHG efficiencies in this study are comparable to those obtained with dielectric AlGaAs nanoantennas [3], whose nonlinear susceptibility is two orders of magnitude larger than the value considered here ($\chi^{(2)} = 6 [\text{pm}/\text{V}]$). This work shows great potential and versatility of plasmonic nanopatch antennas for nonlinear nanophotonic applications.

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References

Modelling the Thermo-Optic Non-Linear Behavior of 2D Photonic Crystal Cavities

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Abstract: We present a first principles model for the thermo-optic nonlinearities of PhC cavities. The match between the calculations and experiments demonstrated here renders the model a crucial predicting tool for the development of nonlinear microcavities. © 2021 The Author(s)

1. Introduction

Photonic Crystal (PhC) cavities have the remarkable ability to confine light at the wavelength scale, with consequent enhancement of the optical non-linearities of a material. This enhanced light-matter interactions become very important for non-linear optical applications in silicon [1]. In the case of thermo-optic non-linearities, this is especially relevant as significant optical power gets absorbed in very small volumes, due to the microcavity high surface to volume ratio enhancing the size-dependent thermal processes. Indeed, at telecom wavelength, the dynamic behavior of optically pumped silicon microcavities is greatly dependent on their thermal properties, mainly controlled by two balancing phenomena:

- The heat generated by optical absorption, either by linear processes such as the absorption related to defect/surface states, and non-linear processes such as two photon absorption (TPA) and free carrier absorption (FCA) mechanisms.
- The heat dissipated from the cavity through the chip, controlled by Fourier’s Law of Heat Conduction.

It follows that a deep understanding of the thermo-optic nonlinear dynamics of PhC cavities allows their most effective exploitation in a broad range of energy-efficient applications based on on-chip bi-stability, such as in fast all-optical switches and memories [2,3]. The thermal response of toroidal microcavities is being discussed in [4], using two characteristic thermal time constants, corresponding to a fast and a slow response, for the experimental data fitting. The fast and slow responses are associated respectively to heat dissipation from the optical volume to the rest of the cavity and from the cavity to the rest of the chip, in a two thermal baths approximation first proposed in [5]. However, this presents an issue as the double exponential decay only approximates the cavity’s thermal response at short timescales (<1μs), failing to match the response accurately at longer timescales, as the thermal volume dynamically changes in time. Furthermore, this double decay approach requires fitting the experimental data to obtain the time constants, lacking the power of cavity response prediction prior to fabrication and testing.

Here we introduce a first principles model that fully describes the thermo-optic nonlinear behavior of optically pumped silicon PhC cavities, in which the spatial temperature distribution of an integrated PhC cavity and chip is calculated in time. The calculated time-space varying temperature represents the material thermodynamics following the confinement of optical energy in the cavity due to a laser beam illuminating the chip. The results shown in this work are for silicon microcavities, but this model can be used for microcavities on any other material just by switching the out the corresponding physical constants. The calculated results obtained offer a realistic representation of the PhC cavity dynamics, demonstrated by their match with experimental data on all relevant timescales (>10μs), eliminating the need to empirically extrapolate time constants from the fitting of the experimental results, also unlocking the possibility to predict the non-linear dynamics of optically pumped microcavities prior to fabrication and characterization.

2. Results and Discussion

The system under investigation is an optically pumped silicon 2D PhC cavity on an SOI chip. In the laser-microcavity system, three main phenomena are dominating the dynamics: part of the light coupled into cavity as resonant mode is linearly absorbed by impurities, defects of the silicon lattice and surface states, and by non-linear processes such as two-photon absorption (TPA) and free carrier absorption (FCA). The subsequent relaxation of TPA and FCA related carriers transfers energy through photon-electron-phonon interactions to the atomic lattice of
the material as thermal energy, which is in turn transferred to the rest of the chip through heat conduction. The plasma dispersion effect generated by FCA decreases the refractive index of the material, balanced by heat generation that increases the refractive index through the thermo-optic effect. These opposite effects allow the microcavity to reach stable and unstable equilibrium states.

In this model, time-varying classical rate equations for optical energy, free-carrier number density, thermal energy density and heat loss rate [6] are used in combination with the calculation of the time-varying temperature spatial distribution in the material through heat transfer equations, to accurately outline the 2D PhC non-linear dynamics. Fig. 2a shows the calculated time-resolved step-response of a DA PhC cavity and Fig. 2b the one of an L3 PhC cavity superimposed to their respective experimentally measured response.

As depicted in Fig. 2, the calculated responses of the DA and L3 cavities accurately match the corresponding measured responses at the same laser-cavity resonance wavelength detuning and pump power in both rapid switch and slow approach to the steady state (at around 10µs).

3. Conclusions

The calculated thermo-optic responses of optically pumped silicon PhC cavities are presented, accurately matching experimental results on both fast (≈ 100 ns) and slow (steady state) timescales. The first principles model introduced has to capability to evaluate the dynamics of PhC microcavities on any type of material just by the using the corresponding physical constants, unlocking the possibility to predict the nonlinear optical behavior of optical microcavities prior to fabrication and characterization, becoming a useful tool for the development of non-linear microcavity-based devices.

4. References

Exploiting time-dependent metamaterials for frequency conversion in guided-wave structures

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Abstract
In this work we study theoretically the effect of using time-dependent metamaterials filling the cladding of optical waveguides and ring resonators as a technique to effectively change the frequency of the wave traveling in such guided-wave structures in real time. The physics behind using such temporal metamaterial clads is discussed and demonstrated numerically at telecommunication wavelengths.

1. Introduction
Metamaterials and metasurfaces [1] have been great candidates for a wide range of exciting applications such as beamforming [2]–[5], sensors[6], [7], invisibility cloaking structures [8], circuits and analog computing [9], to name a few. Such artificial electromagnetic (EM) media have been mainly developed in the frequency domain where their electromagnetic properties are considered to be time-invariant. However, controlling light-matter interaction with time-modulated metamaterials and metasurfaces has started to become a prominent research field given the flexibility in manipulation of fields and waves both in space and time [10]. Time-dependent media was first studied in the last century where step functions of permittivity (ε) and or permeability (µ) were considered [11]. Remarkably, it was demonstrated how wavenumber k does not change after that temporal modulation of ε and/µ. However, frequency is modified from f₁ to f₂ with f₂/f₁ = (ε₂/µ₂)¹/²/(ε₁/µ₁)¹/², (ε₁,µ₁) and (ε₂,µ₂) being the EM parameters before and after the temporal change, respectively [12]. In this realm, time-dependent and space-time metamaterials have been recently studied in exciting applications such as frequency conversion, effective medium concepts in the time domain, anti-reflection temporal coatings, temporal aiming and temporal Brewster angle, inverse prisms [13]–[19], etc. Inspired by the exciting opportunities offered by controlling metamaterials and metasurfaces in both space and time, in this work we discuss and present our recent efforts to apply time-dependent functions of ε for frequency conversion in guided-wave structures by changing in time the relative ε of only a portion of the structure where the wave is traveling (cladding in our case) instead of changing ε for the whole medium.

2. Geometry of the Problem
A schematic representation of the structure is shown in Fig. 1 where an optical ring resonator is presented. The structure is designed at telecom wavelengths (λc = 1.55µm). In our approach, we consider that the core is made with a dielectric with a constant relative permittivity (see schematic in Fig. 1b). However, the cladding is filled with a metamaterial having a time-dependent relative permittivity εclad(t).

In this context, the εclad(t) is rapidly changed in time (with a time duration smaller than the period of the incident wave) from an initial relative value εclad1 to a second relative value εclad2 at t = t₁, see Fig. 1c for a schematic of this time-varying ε. In so doing, it will be shown how a temporal boundary is induced once changing εclad(t). Moreover, it will be discussed how the effective propagation constant (β) of the mode propagating inside the optical waveguide/ring

Figure 1: (a) Schematic representation of the guided-wave structure under study for frequency conversion using a constant relative permittivity for the core (b) and a time-varying relative permittivity for the cladding (c).
resonator remains unchanged while achieving frequency conversion. All the physics behind such frequency conversion technique in guided-wave structures will be discussed during the conference. Moreover, more complex scenarios will also be presented and numerically demonstrated such as multiple frequency conversion using arrays of optical waveguides and/or ring resonators carefully engineered and designed in cascade.

3. Conclusions

In summary, we study a mechanism to achieve frequency conversion in guided-wave structures whose cladding are formed by time-dependent metamaterials. It is numerically shown how the wave propagating inside the cores and claddings undergoes a change in frequency while wavelength and effective propagation constant is not modified. These results may open new paths in the engineering of frequency converters using time-dependent cladded waveguides.

Acknowledgements

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References


Photonic bandgap structures
Phononic band gap of longitudinal acoustic waves in one-dimensional crystal for ultrasonic applications

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Abstract
Nowadays, sensor technology has attracted great interest in various domains. In this work, we have analyzed phononic band gaps of one-dimensional phononic crystal made by a stack of N bi-layers of LiNbO3/SiO2. The transmission spectrum of acoustic waves is calculated by using the transfer matrix method (TMM). The results clearly demonstrate the existence of phononic band gap of which the position and the width are strongly affected by many physical parameters. Our results are useful in various applications such as acoustic barriers and sensor materials.

1. Introduction
Phononic crystals (PnCs) are a new class of materials that exhibit periodic distributions in their density and elastic properties in one, two or three dimensions of space [1]. These structures are called 1D, 2D and 3D phononic crystals respectively. Such crystals allow to modifying the propagation of acoustic/elastic waves and prohibiting the propagation of acoustic/elastic waves in certain directions and frequency ranges [2].
It has long been known that elastic waves cover many wave phenomena in different states of matter: sound in air, acoustic waves in water and liquids, phonons in solids. In recent years, phononic crystals have been inspired much interest due to their potential for controlling the propagation of acoustic waves [3]. Phononic crystal can be used for many different applications such as acoustic filtering, waveguides or sensor applications [4-6].
The aim of this paper is to give an analysis and study of the phononic band gap of the one dimensional periodic structures. Firstly, we have studied the propagation of the longitudinal acoustic waves through 1D-PnCs by two methods; the expanding plane wave (PWE) method adopted for diagram dispersion and the Transfer matrix method (TMM) which adopted for 1D periodic structures. Secondly, using the transfer matrix method (TMM), the transmission coefficients are calculated and plotted for longitudinal waves in order to studying the effects of different physical and geometrical parameters such as the lattice constant, the contrast in densities and the contrast in longitudinal speed of waves in matrix material. Finally, special interest was devoted on the phenomenon of local resonance inside the phononic band gap in order to use such structure for sensing applications.

2. Structure design
The one-dimensional phononic crystal (1D-PnC) structure, which is composed of periodically alternating layers of LiNbO3 and SiO2 with thicknesses of a1 and a2, respectively, is presented in Figure 1. Where a1 is the thickness of the LiNbO3 layer and a2 is the thickness of the SiO2 layer. The lattice constant is a=a1+a2=1mm.

Figure 1: A schematic diagram of a perfect 1D-PnCs

The elastic constants of the matrix and of the inclusions constituting the 1D crystal are illustrated in Table 1.

Table 1: This is an example of a table.

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<tr>
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<th>ρ (kg/m3)</th>
<th>v₁ (m/s)</th>
<th>v₃ (m/s)</th>
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<tr>
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<td>4674</td>
<td>4030</td>
<td>6574</td>
</tr>
<tr>
<td>SiO₂</td>
<td>2600</td>
<td>3370</td>
<td>5840</td>
</tr>
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</table>
3. Results and Discussion

3.1. 1D Phononic band gap

Using the transfer matrix method (TMM) and the plane wave expansion method (PWE) we can calculated the phononic band gap in the case of the propagation of a longitudinal wave. Figure 2 (a) illustrates the transmission spectrum as a function of frequency obtained with TMM method, while Figure 2 (b) shows the dispersion diagram of 1D-PnC. The blue bands represent the phononic prohibited bands which appeared for longitudinal wave.

![Transmission and Dispersion Diagrams](image)

Figure 2: (a) Transmission spectrum as a function of frequency for a longitudinal wave, (b) Dispersion diagram obtained by the PWE method for a 1D-PnC.

3.2. Effects of physical properties

Using transfer matrix method, we are interested to studying the influence of some acoustic/elastic parameters notably the contrast in density and in the speed of longitudinal wave on the properties of phononic band gap.

Figure 3 reports the variations of the phononic band gap properties as a function of density contrast between LiNbO$_3$ and SiO$_2$ materials (red dashed curves). While, the solid green curves show the effects of longitudinal speed in the matrix material on the width and position of the Pn-BG. The results demonstrate clearly that density contrast and longitudinal speed in matrix have a great influence on the location and bandwidth of Pn-BG.

![Band Gap Diagrams](image)

Figure 3: (a) width and position of 1D phononic band gap as a function of density contrast (red curves), (b) variations of 1D Phononic band gap properties as a function of longitudinal speed in matrix material (green curves).

4. Conclusions

In this work, an analysis of a perfect 1D-PnCs formed by the stack of 10 bi-layers of LiNbO$_3$/SiO$_2$ has been studied, using transfer matrix method and PWE method.

The various calculations show clearly that the physical properties; in particular density contrast and the longitudinal speed in matrix material have a great influence on the position and on the size of phononic band gap which proves the ability to use the 1D-PnCs with defect in sensors applications.

References


Three-Dimensional Photonic Crystal Composites with High Refractive Index Thin Films

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Abstract

We study polymer photonic crystals coated with varying thickness of high refractive index material aiming to make functional photonic devices capable of controlling light through band structure and dispersion. We observed red shifts of partial bandgaps in the near infrared region when the thickness of deposited MoS₂ films increases. A ~150 nm red shift of the fundamental and high order bandgaps is measured after a ~15nm thick MoS₂ coating.

1. Introduction

High refractive index contrast photonic crystals show bandgaps blocking light propagation in all directions. Starting from a low index template and depositing high index material, we can open and enlarge bandgaps and control the dispersion. Here, such refractive index composites are fabricated by coating polymer three-dimensional (3D) woodpile structures (see Figure 1) with thin molybdenum disulphide (MoS₂) films. A two-step process is used: 3D polymer woodpile templates are fabricated by a direct laser writing (DLW) method followed by chemical vapour deposition (CVD) of MoS₂ [1]. The optical properties of the composite structures are examined by measuring reflection spectra changes after each 2 nm thin film coating via our angle-resolved Fourier imaging spectroscopy (FIS) system [2-4].

2. Fabrication

A direct laser writing (DLW) system based on the two-photon polymerization (2PP) method is used to fabricate woodpile photonic crystals in a photoresist (IP-L) [2]. The laser beam is produced by a femtosecond fibre laser and the beam is focused through an oil-immersion objective lens with an NA of 1.4 and 100× magnification into the photoresist. Figure 1 (a)-(c) illustrates the thin film coating of these woodpile templates and (d) shows an SEM image of the fabricated woodpile template. The dimensions of the fabricated body-centered cubic (BCC) woodpile [5,6] are vertical period c and lateral rod distance a, c = a =1µm, rod height h ~ 580 nm, rod width w ~ 240 nm. The sides of the structure are open, ensuring that the gas flow can get in providing even coatings. The lattice constant c is chosen to give a starting bandgap around 1.2-4 µm so that it moves into the 1.5-1.6µm range after high refractive index material deposition.

![Figure 1: Schematics of (a) non-coated woodpile template (b) thin film MoS2-coated woodpile template (c) resulting rod cross section after each 1nm MoS2 thin film coated. Colours (red, green and blue) are used to indicate the 1nm thin films coated in sequence. (d) SEM scanning image of the fabricated woodpile template.](image)

We perform chemical vapour deposition (CVD) of MoS₂ thin film on our fabricated polymer woodpile templates to achieve high refractive index contrast composites. Thin film deposition for 30 mins at room temperature followed by annealing treatment at 250° C for 3 hours achieves a ~2 nm MoS₂ deposition while avoiding any obvious thermal deformation of woodpile templates.

3. Simulation and Measurement Results

To visualize the modification of the photonic bandstructures, angle-resolved reflection spectra after each thin film deposition are measured via our angle-resolved Fourier imaging spectroscopy (FIS) system [2-4]. Figure 2 plots the measured angle-resolved reflection spectra for bcc woodpile structures with varying MoS₂ thickness (0-15nm). The angles in Figure 2 correspond to the collection angle relative to the Z direction, in the YZ plane (See Figure 1(a)). Photonic band calculations for the corresponding directions were also done using the following refractive index values: n(IP-L)=1.52 and n(MoS₂)=3.1.
4. Discussion

Figure 3a shows the measured spectra at normal incidence (solid lines) and simulated results using the PWE method. The simulations show (figure 3b) a 6 nm red shift of the fundamental bandgap (at ~1.3 μm) at normal incidence after the first 2 nm MoS₂ thin film coating (red dashed line), followed by another 12 nm and 14 nm red shift after the second (green dashed line), and the third deposition (blue dashed line). For the measurement, a clear red shift of the lower edge of the bandgap after the first (~10 nm, red solid line) and second (~12 nm, green solid line) deposition can be observed. However, the red shift after the third deposition (blue solid line) is not obvious. To have more easily observable shift, we coated ~15nm MoS₂ film onto a bare template. The red shift between non-coated and 15 nm coated is around 150 nm which is relatively large compared to previous data. The result is presented in Figure 3 (a), purple solid line for measurement and dash line for PWE simulation.

5. Conclusions

Polymer woodpile templates are fabricated, and we managed to measure partial bandgaps at near infrared region. We observed a ~10 nm red shift of bandgaps after each 2 nm MoS₂ thin film deposition and ~1.3 μm red shift for the ~15 nm MoS₂ coated. Simulation results also show red shifts of bandgaps with increasing deposition thickness and optimized gap-midgap ratio. By measuring the red shifts of bandgaps, one can determines the thickness of depositions via comparing with calculations. Thus, this optical method can also work as an alternative way to measure the thickness of deposited films without contacting or damaging the films.

Acknowledgements

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Fabrication of 1-D Photonic crystals to enhance thermochromic properties of VO₂ nanostructures

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Abstract

Effect of 1-D photonic crystals on optical transmission of VO₂ is studied by depositing VO₂ thin films on Distributed Bragg Reflectors (DBR) in the infrared (IR) spectrum. Monoclinic VO₂ nanoparticles were first synthesized by solution processed method. VO₂ nanostructures of varying crystallinity were formed by changing ambient and annealing conditions. By combining VO₂ films on DBR structure, the average optical transmission approaches to zero in the IR region in and above the critical temperature 68°C. which could be the positional design for VO₂ nanoparticles based hybrid Photonic absorbers for various smart window applications.

1. Introduction

Monoclinic Vanadium dioxide VO₂ (M) is a dark blue black crystalline material which undergoes a crystalline phase transformation around 70° C. The crystal structure changes from monoclinic M1 phase to tetragonal R phase [1]. This metal to insulator (MIT) transition from above and below ~ 70°C leads to predominant changes in its optical and electrical properties[2]. Thus thermochromic VO₂ films caught a wide attention in smart widow applications for energy efficient buildings [3-4]. Due to this MIT transition there is a drastic a changes from infra-red (IR) blocking metallic state to IR transparent semi conductive state [5], with change abrupt in electrical properties [6]. Such excellent properties also makes VO₂ a promising candidate for smart window coating and IR based absorbers [7]. There are consolidated efforts to achieve enhanced properties of VO₂ based hybrid device architecture.

Here we describe one such hybrid device architecture based on 1-D photonic crystals. These 1-D photonic crystal are one of the most important structures to achieve optical control by localizing light modes [8] and by controlling the flow of light [9]. This consists of a photonic crystal having one dimensional periodic array of multilayers of two materials with different dielectric constants having very high reflectivity. This is commonly known as Distributed Bragg reflector (DBR). Such 1-D photonic crystal paved a new path for novel efficient hybrid design for optical absorbers across the electromagnetic spectrum. There are many reports where Bragg reflector based absorber has been studied [10]. 1D Photonic crystal were studied in order to achieve perfect absorption due to localized photonic modes.

Here, 1D photonic crystal based VO₂ perfect absorber is proposed to enhance the absorption near to unity in IR range over MIT phase transition. Here we have implemented a 1D photonic crystal based Distributed Bragg reflector fabricated with SiO₂ / TiO₂ alternating structure with VO₂ (M) nanostructures composite. Performance VO₂ nanostructure with Bragg reflector were shown. Such, 1D photonic crystal based VO₂ thin films are proposed to enhance the absorption near to unity in IR range.

1.1 Figures
2. Discussion

The optical transmission spectra if VO₂ thin film formed with PVA nanocomposite on glass is shown in Fig. 1. With increase in temperature there is reduction in transmission from 52 to 43 % at 1600 nm when temperature varies form 300 K to 380 K. Fig. 2 shows the same thick VO₂ film on 1D Photonic crystal leads to nearly vanishing transmission at 1600 nm.

3. Conclusions

In summary, VO₂ (M) was synthesized by thermyolsis method. By depositing VO₂ over DBR , results in the formation a DBR having a stop band at 1600 nm with nearly vanishing transmission. Employing a 1-D Photonic crystal with VO₂ films as hybrid optical absorber leads to near ideal enhancement of effective optical absorption. Hence such hybrid structures are potential candidates for designing VO₂ based optical absorbers for smart windows and IR sensors. Further work is going on to tailor these VO₂ nanoparticles to lower this metal-insulator transition temperature of 68 °C towards room temperature for ambient operations.

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Hybrid External Cavity Laser based on Silicon Nitride 1D Photonic Crystals Cavities for optical sensing in gasses and liquids

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Abstract

In this paper we demonstrate a 1D silicon nitride photonic crystal cavity for optical sensing operating in the NIR wavelength range. The device consists in a photonic crystal cavity side-coupled to an S-bent waveguide, leading to a good coupling efficiency and allowing its fabrication through a single etch of a uniform layer of SiN, deposited on bulk silicon and cladded in oxide. The cavity shows resonances in the wavelength interval 1060-1090 nm with maximum measured Q-Factor in the range of $10^4$ and a Free Spectral Range (FSR) of 10 nm. The possibility to control its Q-Factor, varying the etching angle of its sidewalls, over a range of refractive indexes and the SiN biocompatibility and transparency in the visible and NIR spectrum unlocks the possibility to use these photonic crystal cavities in both air and liquids, paving the way to a new family of chip integrated, highly sensitive and mass manufactured sensors and biosensors for liquid and gas analytes.

1. Introduction

In the last few years, the ever-growing investigation of fast and label-free optical biosensing led to a wide range of applications, from viruses and bacteria detection to environmental monitoring of pollutants. Current technologies include: nanoscale sensors, such as nanowires and plasmonic particles, presenting a relatively small capture area, hindering analyte detection \cite{1,2} and mechanical cantilevers, commonly used for sensing in air or vacuum but not employable in liquids due to oscillations dampening \cite{3}. Whispering-Gallery Mode (WGM) optical resonators offer high speed and sensitivity for label-free sensing, but suffer from chip integrability and multiplexing possibility for their size \cite{4}. A developing solution for label-free biosensing is presented by optical devices based on photonic crystal cavities, as they are characterized by (i) very low losses and small footprint, but larger capture area compared to nanoscale sensors, and (ii) flexibility and great on-chip integrability, as opposite to WGM optical sensors. Here we demonstrate a Hybrid External Cavity Laser (EC) based on 1D Si3N4 photonic crystal cavity that could be employed in optical sensing in the NIR spectrum. The device consists in a reflective semiconductor optical amplifier (rSOA) edge-couple to an S-bent waveguide evanescently exchanging energy with a 1D photonic crystal cavity, offering a good coupling efficiency and allowing its fabrication through a single etch of a deposited and uniform Si3N4 layer, then cladded in oxide. The cavities show resonances in the wavelength range of 1060-1090 nm with measured Q-Factors in the range of 104 and an average Free Spectral Range (FSR) of 10 nm. The control over the cavities Q-Factor changing the etching angle of their sidewalls \cite{5}, over a broad range of refractive indexes \cite{6} and the Si3N4 biocompatibility and transparency in the visible and NIR spectrum allow the employment of these devices in both air and liquids, unlocking the development of a new set of chip integrated, highly sensitive and mass manufactured label-free optical sensors for liquid and gas analytes.

In this paper we demonstrate numerical results for SiN 1D photonic crystal (PhC) cavities operating in the 1000 nm range, showing very high Q factor for a broad range of refractive indexes (from 1.10 to 1.45) of the upper-cladding due to the engineering of the cavity sidewalls angles. Sensitivity and figure of merit of the PhC cavities are also discussed. Moreover, fabrication and experimental results of the cavities are shown for devices operating in the 1000 nm and the 1550 nm range. The high experimental Q factors associated in all the different upper-cladding configurations unlock the possibility to use this arrays of these devices as label-free optical sensors for both gasses and liquids.

2. Device Concept

Figure 1 shows the schematics of one of the SiN 1D photonic crystal cavity side coupled to the waveguide. The SiN waveguide is butt-coupled to a reflective semiconductor optical amplifier (rSOA) in hybrid external cavity configuration \cite{7}, to output the lasing line selected by the resonant 1D PhC cavity. The SiN cavity has been designed to be very sensitive to the refractive index of the environment surrounding it, thus the varying its spectral response depending on the refractive index in which it is immersed. The change in refractive index of the upper-cladding due to the concentration of determined compound...
in a gas or liquid solution shifts the wavelength of the PhC cavity reflection peak, which results in a wavelength shift of the external cavity laser line. Hence, the solution concentration is directly related to the measurement of the shift of the laser wavelength, as in the schematics shown in Figure 2.

Moreover, the reduced footprint on chip of the 1D photonic crystals, 30 μm long by 2 μm wide, makes this type of device compatible with high integration densities and compact packaging solutions.

3. Experimental Results and Discussion

The 1D photonic crystal cavities have been designed to have a Q factor higher than $10^5$ with a broad range of upper-cladding refractive indexes from 1.15 to 1.5, which represents the majority of liquids, as shown in Figure 3.

The transmission spectra of the 1D photonic crystal cavities operating in the 1060 - 1090 nm wavelength range have been collected through an end-fire setup, in which the light of a super luminescent LED propagates through an optical fiber, is collimated into the SiN waveguides on the sample through a system of lenses, and is then collected at the output of the waveguides in an optical spectrum analyzer and a photodiode.
4. Conclusions

To conclude, we have demonstrated a new type of SiN 1D photonic crystal cavity operating in the 1060-1090 nm wavelength range with Q-factors higher than 105 over a broad range of upper-cladding refractive index (1.15 to 1.50) which can used in a hybrid external cavity laser configuration to operate as a label-free optical sensor in most gasses and liquids.

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References


Self-assembled Photonic Crystals for Colorful Radiative Coolers

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Abstract
Recently, radiative cooling has been actively studied, as objects can be cooled without using additional energy. Here, we demonstrate a new class of radiative cooler, this is silica photonic crystals, which are used for the structural colorization. The intrinsic phonon vibration of silica leads to the absorption of mid-infrared (mid-IR) waves, which in turn cool the objective in a radiative way. At daytime, these assembled photonic crystals effectively reduce the temperature of the crystalline-silicon (c-Si), while maintaining appearing colors.

1. Introduction
Passive radiative cooling is a very useful technique, because it can cool an object without energy consumption. Previous, the use of radiative coolers benefitting from the intrinsic phonon-mediated absorption/emission of mid-IR (i.e., silica and silicon nitride) had been limited at nighttime, as the solar absorption could lead to the significant increase in temperature [1]. However, recently, the implementation of nanophotonic solar reflector into such conventional materials has greatly expanded the nighttime-limited radiative cooling to the daytime counterpart [2,3,4,5,6]. In the initial state of this daytime radiative cooling, the studies had been more oriented toward increasing the performance of broadband solar reflections, so that the colors of the developed radiative cooler are very limited to white or silver [3,4]. However, the aesthetic purposes (e.g., building paints with the functions of passive cooling), in case, demand the colorization of radiative cooler. To address this technical challenge, several strategies have been suggested, but all these previous methods were restricted on absorption-based colorization [5,6]. As such, the radiative coolers with these colorizations cannot avoid the solar-heating effect.

Here, we have developed the opalline radiative coolers, which simultaneously enable radiative cooling and reflection-based colorization in the visible regime. Fig. 1 shows the process for the large-area self-assembly of silica nanobeads (200 ~ 300 nm in diameter) into the close-packed face-centered-cubic (FCC) crystals, which are generally referred to opals. The self-assembled silica photonic crystals can show vivid colors originating Bragg diffraction at the visible regime. The structural unit of silica photonic crystals is deep-subwavelength-scale at the mid-IR regime, in which thermal radiation dominantly occurs. Therefore, in the mid-IR range, the silica photonic crystals can be considered as homogeneous medium; thereby, acting as a thermal metamaterial with an ability to radiatively cool an object.

2. Self-assembly of photonic crystals
We synthesize silica nanobeads in a one-step synthetic process (denoted Stöber method) [7]. During this synthesis, adjusting the volume of ethanol enables the precise control over the size of silica nanobeads from 200 nm to 300 nm. A thin polydimethylsiloxane (PDMS) polymer layer with a thickness of less than 5 μm is used to promote the adhesion between c-Si substrate and silica photonic crystals. On the 3 cm by 3 cm c-Si substrate, the silica nanobeads are self-assembled into the photonic crystals through gravity sedimentation.

![Image](image.png)

Figure 1: The process of self-assembly of photonic crystals. By gravity, nanobeads are self-assembled on the substrate.

3. Results and discussion
The wavelength of the Bragg reflections along the normal direction of the photonic crystals (i.e., (111) direction) can be defined as follows: [8]

\[
2d \sin \theta = n\lambda
\]  

(1)
where \( d \) is the interplanar distance, \( \theta \) is the glancing angle, \( n \) is the positive integer, and \( \lambda \) is the wavelength of the incident wave. Thus, the photonic crystals, self-assembled from 200 nm, 240 nm, and 290 nm silica nanobeads, can appear bluish, greenish, and reddish colors, resulting from Bragg reflection. Actually, the photonic crystals assembled from these silica beads exhibit the expected reflection peaks, as presented in Fig. 2a: peaks at 460 nm wavelength for bluish, 520 nm wavelength for greenish, and 630 nm for reddish colors. Thus, we can achieve non-absorbing structural colorization via Bragg reflection, which in turn minimize the solar absorbing effect.

More importantly, it is noteworthy that our photonic crystals absorb a significant amount of mid-IR waves, especially at 8–13 \( \mu \)m of wavelengths (Fig. 2b). These abilities of photonic crystals to absorb mid-IR waves implies that the stored thermal energy should be equally emitted (i.e., radiative cooling) according to Kirchhoff’s law. The volume fraction (vol\%) of nanobeads in FCC lattice can be up to 74 regardless of bead size. Consequently, the absorption and emission of mid-IR waves should be consistent across the self-assembled photonic crystals. However, these mid-IR absorptions from three different photonic crystals are slightly different, possibly originating from the structural imperfections. With respect to the working wavelength, our photonic crystals can play dual roles: (i) reflective structural color pigment at the visible and (ii) radiative thermal loader/emitter at the mid-IR.

Fig. 3 shows representative results of the daytime-traced temperature measurements of photonic crystal-coated c-Si. Several important features are noteworthy: (i) the photonic crystals can considerably reduce the temperature of c-Si at the daytime regardless of structural colorizations and (ii) the cooling efficiency slightly varies across the assembled photonic crystals, resulting from their non-consistent efficiency of Bragg reflection.

4. Summary

In summary, we have presented an undiscovered usage of photonic crystals for colorful radiative cooling. In contrast to the previous approaches for colorful radiative cooling, self-assembled photonic crystals lead us to achieve the non-absorbing colorization at the visible, while simultaneously enabling efficient radiative cooling at daytime. Indeed, the temperature of the target substrate (i.e., widely used solar absorber) is reduced by 15°C during the daytime, while keeping the colors. Their soft fluidity of the process in conjunction with high performance can facilitate the use of self-assembled photonic crystals for immediate practice applications.

Acknowledgements

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Spatial Filtering Enabled Spectral Characterization of a Photonic Crystal Cavity
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Abstract

We experimentally demonstrate a technique to estimate resonance wavelength of a photonic crystal cavity by spatially filtering a laser beam incident at different angles and imaging the transmitted beam profile. The transmitted beam exhibits two features: an annular beam and a central spot. Under the resonance condition, the two features overlap spatially. We develop calibration curves for the spectral characterization using transfer matrix method. The estimates from our cost-efficient technique match well with measurements obtained using a spectrophotometer.

One-dimensional photonic crystal cavities are widely used to design many on-chip optical components including optical switches [1], sensors [2], optical filters [3], light-emitting diodes [4], and lasers [5]. These structures are fabricated by depositing alternate thin-films of two different dielectric constants with a cavity in between by various techniques such as sputtering, evaporation, and sol-gel. To optimize these fabrication processes, the samples are typically characterized using a spectrophotometer. However, a spectrophotometer is an expensive and sophisticated tool. Here we experimentally demonstrate a cost-efficient technique to estimate the resonance wavelength of a one-dimensional photonic crystal cavity using spatial filtering of a laser beam. We observe the transmitted beam at broad range of incidence angles. The transmitted beam has two key features: an annular beam and a central spot. We estimate the resonance angle as the incidence angle at which the maximum transmission occurs. The resonance angle is also visually evident (for visible laser wavelengths) because at this angle the two key features of the transmitted beam overlap spatially. We relate the resonance angle to the resonance wavelength of the cavity using transfer matrix method (TMM). Apart from research laboratories, our simple and economical technique can also be used in teaching laboratories at high-school and undergraduate levels, particularly in developing countries.

Figure 1a shows a schematic of the one-dimensional photonic crystal cavity used in this work, which consists of a SiO\textsubscript{2} spacer layer of length \(L\approx 250\) nm between two distributed Bragg reflectors (DBR) that consist of six alternating layers of SiO\textsubscript{2} and TiO\textsubscript{2}. The refractive index and thickness of SiO\textsubscript{2} (TiO\textsubscript{2}) layer are 1.46 (2.05) and \(\approx 110\) nm (80 nm) respectively. We deposit all layers using radio-frequency magnetron sputtering system on a glass substrate. Figure 1b shows a transmission spectrum of the sample with stopband from \(\sim 560-770\) nm and cavity resonance at 672 nm at normal incidence measured using spectrophotometer (Perkin Elmer Lambda-950). The cavity resonance wavelength shifts to a lower wavelength with an increase in the angle of the incidence. This property allows us to track the optimum angle of incidence, defined as resonance angle, at which transmission of an incident laser maximizes. The resonance angle is directly proportional to the difference in the cavity resonance wavelength at normal incidence and the incident laser wavelength, which allows us to convert the resonance angle to the resonance wavelength of the cavity. Figure 1c shows a schematic of the optical setup used for estimating the resonance angle. We incident a linearly polarized laser at wavelength of 632.9 nm with a Gaussian mode-profile on our fabricated sample mounted on a rotational stage. The rotational stage allows us to change the angle of incidence by rotating the sample with respect to the laser beam. The transmitted beam is projected on a screen and captured using a camera. Both the screen and the camera are attached to the rotational stage such that the sample, the screen, and the camera planes are parallel to each other.

Figure 2a shows observed intensity profiles of the transmitted beam for different angles of incidence, ranging between \(0^\circ - 46^\circ\), of the laser beam on the fabricated sample. At normal incidence, though the incident laser wavelength (632.9 nm) is in the stopband of the photonic crystal cavity (Fig. 1b) and away from the cavity resonance (672 nm), the bright spot is due to weak transmission (0.002 in Fig. 1b) of the incident beam in the stopband that we attribute to finite

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{(a) Schematic of a one-dimensional photonic crystal cavity with spacer length \(L\). (b) Experimentally measured transmission spectrum of a cavity at normal incidence, using a spectrophotometer. (c) Schematic of the optical setup.}
\end{figure}
number of periods in the fabricated sample. Also, due to Gaussian spatial profile of the beam, a small fraction of the wave-vectors are present at the resonance angle that transmit through and result into a faint ring at normal incidence due to the in-plane symmetry of the structure. As we rotate the sample (least count = 2°) and increase the angle of incidence, the intensity of the ring increases because the fraction of wave-vectors satisfying the resonance angle condition is increasing, and the bright spot moves closer to the periphery of the ring. At incidence angle 32°, the ring has the highest intensity and the bright spot overlaps with the periphery of the ring. As we further rotate the sample, the intensity of the ring decreases and the center spot moves further away from the ring. We calculate average transmitted intensity of the ring profile by considering seven different locations on the ring (away from the saturated spot) as a function of incidence angle and show normalized transmission spectrum in fig. 2b by red curve that peaks at 32°. We also calculate normalized transmission spectrum of a plane wave (632.9nm) as a function of the incidence angle through the photonic crystal cavity structure using TMM (dashed curve in Fig. 2b). Both the experiment and the calculation predict the same resonance angle of 32° for the fabricated sample. We observe that the width of the resonance peak is more in experimental data than in the simulated data, which can be improved by increasing resolution in stage rotation.

Next, we calculate a calibration curve to convert resonance angle (determined in Fig. 2b) to resonance wavelength of the photonic crystal cavity that is under characterization using 632.9 nm laser. The resonance wavelength of the photonic crystal cavity depends on thickness of the cavity layer and thicknesses of the layers in the DBRs, all of which can vary during fabrication. We account for these variations in our calibration curves. We first calculate the required resonance angle for transmission of a 632.9 nm laser through an ideal structure designed to have both stopband and cavity resonance centered at 670 nm, using TMM. By fixing the thicknesses of layers in the DBR, we vary the cavity layer thickness and obtain resonance angles as resonance wavelength of the structure changes, as shown in fig. 2c by the black solid curve. Similarly, we calculate resonance angle as a function of resonance wavelength for ± 5% change in thicknesses of the layers in the DBR (the green and blue curves in Fig. 2c) that changes the center wavelength of the stopband to 703 nm and 636 nm. Using Fig. 2c, experimentally obtained resonance angle of 32° corresponds to resonance wavelength of 669 ± 3 nm at normal incidence. This estimate is in good agreement with the resonance wavelength obtained using a commercial spectrophotometer (Fig. 1b).

In conclusion, we demonstrated an economical spectral characterization technique for one-dimensional photonic crystal cavities that find widespread use in various device applications. Our technique determines the angle of incidence at which transmission of a laser beam maximizes through the structure and estimates the resonance wavelength from it. We also account for fabrication related non-idealities in our estimation. The estimates from our technique show good agreement with the values obtained using a commercial spectrophotometer.

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Self-action of Bloch surface waves in a one-dimensional photonic crystal

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Abstract

Bloch surface waves (BSWs) in one-dimensional photonic crystals are considered as a promising platform for two-dimensional integrated optics and optical manipulation of particles. In this contribution, we present an experimental study of nonlinear optical effects that occur when BSWs are excited at the interface with a water suspension of dielectric nanoparticles. The results are in agreement with our theoretical predictions and highlight the potential of BSWs for use in two-dimensional devices operating in a nonlinear regime.

1. Introduction

Bloch surface waves (BSWs) are propagating modes supported by periodic structures and localized at their interface. BSWs in one-dimensional photonic crystals are in many ways analogous to surface plasmon polaritons in metal films and have been widely used for sensing applications [1, 2]. In contrast to surface plasmons, BSWs are typically excited in all-dielectric structures possessing negligible losses. Moreover, their dispersion can be varied by changing geometric parameters of the photonic crystal used [3]. Due to these properties, BSWs are currently being considered as a potential platform for two-dimensional integrated optics [4, 5].

Recently, BSWs in one-dimensional photonic crystals have been proposed as an alternative tool for optical manipulation of particles. It has been experimentally shown that dielectric microbeads located in the BSW evanescent field experience a force that keeps them near the photonic crystal surface and makes them move in the direction of BSW propagation [6, 7]. Three-dimensional trapping and in-plane manipulation of metal nanoparticles have been demonstrated using focused BSWs [8].

Optical forces acting on polarizable objects in a non-uniform optical field cause a huge nonlinearity of nanoparticle suspensions [9, 10]. When a continuous-wave laser beam propagates through a concentrated liquid suspension, the particles tend to localize in the beam, thus increasing the effective refractive index. As a result, Kerr-type nonlinear optical effects can be observed using relatively low optical powers [11, 12].

In this contribution, the nonlinear behavior of BSWs propagating at the interface with a water suspension of polystyrene nanoparticles is studied.

2. Methods

The photonic crystal under study consists of four pairs of quarter-wavelength layers of Ta$_2$O$_5$ and SiO$_2$ with the first bandgap central wavelength of 1.3 µm. BSWs are excited in the Kretschmann configuration scheme using continuous-wave laser at 638 nm. The excitation beam is slightly focused on the photonic crystal surface with the full divergence angle of approximately 0.4°. As a nonlinear medium, we use a water suspension of 47-nm polystyrene nanoparticles with a concentration of 25 mg/ml. The BSW excitation is experimentally revealed using angular reflection spectroscopy and naturally visualized due to light scattering at the nanoparticles.

3. Results and Discussion

First, we observe the modification of the BSW resonance with increasing excitation power. At a power as low as 20 mW, the angle of minimal reflectance shifts by more than 0.3° which is close to the angular width of the resonance.

Second, we observe self-focusing of BSWs. At a power of approximately 50 mW and a slightly off-resonant angle of incidence, the BSW is focused at a distance of approximately 220 µm from the incident beam waist.

These observations are in agreement with our theoretical predictions based on the calculations performed with a plane-wave model. In theory, however, one could also expect bistable behavior of BSW excitation, which is not observed experimentally. The reason of that may be attributed to the intrinsically three-dimensional nature of the nonlinear BSW propagation.

4. Conclusions

BSWs in a one-dimensional photonic crystal have been shown to experience nonlinear self-action effects at extremely low power values due to the multiple field enhancement at the BSW resonance. Self-induced resonance shift and focusing of BSWs have been experimentally observed. The results highlight the potential of BSWs for use in two-dimensional devices operating in a nonlinear regime.

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References


Near-field optical investigation of Hyperuniform Disordered photonic structures

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Abstract

Located in-between random structures and perfectly ordered photonic crystals, there is a special class of disordered heterostructures called hyperuniform disordered (HuD) photonic structures. These materials, due to the presence of a photonic bandgap, combine the advantages of disordered systems and ordered systems: here, we underline and experimentally prove all these advantages by means of the first near-field optical characterization of HuD photonic structures in the near IR.

1. Introduction

Disordered photonic nanostructures have attracted a lot of interest in the past decades, due to the fascinating, complex and elusive physics of random media, but also in addition to a wealth of interesting applications based on light-matter interaction and light controlling. Whereas periodic structures suffer from limited rotational symmetries, disordered and aperiodic geometries can be more isotropic, leading to superior optical functionalities such as scattering-induced light localization, light extraction from the light emitting diodes (LED), and omnidirectional absorption for solar applications. Located in-between random structures and perfectly ordered photonic crystals, there is a special class of disordered photonic heterostructures, called hyperuniform disordered (HuD) photonic structures [1,2]. These systems have recently been shown to display large isotropic band gaps (BG) as well as optical transparency, to mention two of the most fascinating an promising features. In particular, HuD systems may show BGs comparable in width to the ones found in photonic crystals, thanks to the underlying point-pattern template upon which the structures are built. In particular, a point pattern in real space is hyperuniform if, within a spherical sampling window of radius R (in d dimensions), the number variance $\sigma(R)^2$, for large R grows more slowly than the window volume (i.e. more slowly than $R^d$). This means that in Fourier space the structure factor, $S(k)$, approaches zero as $|k|$→0, which is the reason of transparency at long wavelength. In addition, HuD systems share with disordered systems the presence of Anderson localization for light with quite small modal volumes for states at the borders of the BG. The additional advantages of HuD with respect to random systems is the prediction of resonances with low loss and relevant mode steadiness to external perturbation. It follows that, given the lack of periodicity in HuD solids, Bragg scattering is not a prerequisite for photonic band gaps; interactions between local resonances and multiple scattering are sufficient, provided that the disorder is constrained to be hyperuniform. Broadband k-space control, combined with rotational symmetry and with the possibility of systematically generate these patterns through a specific design rule via universal tessellation protocol, elevates HuD systems at the center of an innovative field of photonics applications, combining the advantages of both random and ordered structures.

Pioneering experiments on photonic HuD systems have explored IR light diffraction in 3D dielectric structures [3], along with visible light scattering experiments from HuD plasmonic gold surfaces [4]. Here we report the first near-field optical mapping and spectroscopy of Anderson modes at telecom wavelengths in a HuD photonic system, consisting in a double membrane photonic structure.

2. Investigated structure and experimental setup

The investigated system is a HuD dielectric structure on two GaAs parallel membranes [5] with air circular holes following a specific pattern; the design is derived from a stealth hyperuniform point pattern with a stealthiness parameter $\chi = 0.5$ (where $\chi$ is defined as the ratio between the number of $k$ vectors for which the structure factor $S(k)$ is constrained to vanish and the total number of $k$ vectors). The vertical etching assurs that the holes patterns in the two parallel membranes have the same nominal design. Figure 1a shows the top view scanning electron microscopy (SEM) image of one of the investigated samples, with lattice constant, $a=360nm$, and filling fraction $\theta=0.27\%$. From the SEM images, we measured both the slab thickness and the inter-membrane separation distance, that resulted to be respectively $t=130nm$ and $d=105nm$. High density InAs quantum dots (QDs), whose ground state is centered at 1300nm, are embedded in the middle of the upper membrane, and act as optically active medium. A room temperature commercial SNOM Twinsnom, OMICRON is used in an illumination-collection geometry. The sample is excited with light from a diode laser (785 nm) coupled into a chemically etched optical fiber, which allows us to have a direct measurement of the LDOS of the system. Infact
photoluminescence (PL) spectra from the sample are collected at each tip position through the same probe.

3. Preliminary results and discussion

Figure 1 reports a summary of the data obtained by the SNOM experiment. In fig.1b we show a typical PL spectrum (in blue) of the HuD structure at a specific tip position, where several sharp resonances are clearly visible. These resonances are spectrally sparse over the full emission range of the QDs, (reported in the same graph in yellow), with quality factors (Q) ranging from 400 to 1000. We were able to calculate the PL enhancement spectrum at every tip position by dividing the recorded spectrum by the QDs PL spectrum. In this way it was possible to reconstruct the near-field spatial distribution of the PL enhancement over a broad range of wavelengths (1165-1280 nm), which reflects the distribution of the electric field intensity: this collective map, reported in fig.1c, allows us to visualize the high spatial density of modes that exhibit a very high PL enhancement (of the order of 15). Preliminary measurements show modes that, if located sufficiently far from the borders of the structure, can exhibit quite high Q factor if compared with the values of Q=100-200 found in randomly designed similar photonic structures [5]. Unperturbed HuD systems, similarly to other conventional disordered structures, display defect modes. These Anderson-like localized modes occur naturally at the PBG edges, extend over five to ten cells, and are easily distinguishable as below and above the PBG due to the electric field being concentrated in the dielectric and in air. Differently from defect modes arising from disorder, we found that the modes here investigated show steadiness features and resilience to fabrication imperfection. In fig.1d we report the spectra, obtained from two nominally identical structures, acquired in the position of maximum intensity of the electric field of a selected mode. The insets are the PL maps at the central wavelength of the two peaks. The two spectra (orange and red for the two replica) shows a spectral similarity that, combined with the almost identical spatial footprint visible in the corresponding PL maps, makes the effect of fabrication induced disorder almost negligible.

4. Conclusions

In this work we present the first near-field optical investigation in the near IR of a HuD photonic system. We show that these materials, due to the presence of a photonic bandgap, combine the advantages of disordered systems and ordered systems. Like random structures they exhibit a large plethora of photonic modes with high spatial density. However, while their statistical properties are robust against fabrication induced disorder, they are deterministic materials in the sense that it is possible, after theoretical calculations, to predict where light localization will take place experimentally, both spatially and spectrally. Moreover, the Q factors of the optical cavities arising from light localization that were experimentally detected are one order of magnitude larger than in the case of disordered systems.

References

Photonic hypercrystal (PHC) has derived the name from photonic crystal (PC) and hyperbolic metamaterial (HM). It is a relatively new member of the family of metamaterials. A sub wavelength periodic variation of the hyperbolic metamaterial gives rise to the formation of photonic hypercrystals [1–9]. Naturally occurring or fabricated hyperbolic metamaterials are characterized by the presence of high-k propagating waves (evanescent waves in free air). Since these high-k waves lie outside the light cone and can be made to suffer Bragg diffraction by periodically varying the width or permittivity of one of its component layers (metallic or dielectric layer). From the emergence of the idea of photonic hypercrystal, a very active research is being carried out on its theoretical as well as experimental aspects. Here we theoretically investigate the wave propagation in two different types of photonic hypercrystals; one is based on $\text{In}_{0.55}\text{Ga}_{0.47}\text{As}:\text{Al}_{0.48}\text{In}_{0.52}\text{As}$ semiconductor superlattice that shows hyperbolic dispersion in mid infra-red region and the other is based on $\text{Ag}/\text{TiO}_2$ sub wavelength layered structure considered as hyperbolic metamaterial in visible region. The emergence of different types of transmission gaps in frequency as well as in momentum space and some of the characteristics of these gaps such as their dependence on filling ratio of HMM and angle of incidence is studied by curve plotting and simulations.

Fig.1 (a) The metallic gap and the plasmon-polariton (PP) gap in a PHC based on 50 percent filling ration of $\text{In}_{0.55}\text{Ga}_{0.47}\text{As}:\text{Al}_{0.48}\text{In}_{0.52}\text{As}$ HMM. (b) the dependence of PP gap on the angle of incidence.

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Photonic liquid crystal fibers with gold nanoparticles-doped cubic blue phases for enhanced electric field tunability and thermal stability

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Abstract

In this work, optical properties of photonic crystal fibers infiltrated with gold nanoparticles-doped cubic blue phases liquid crystals are demonstrated. It is presented that the investigated complex photonic systems can provide promising tunable properties for particular wavelengths in the visible light spectrum. Moreover, the presence of gold nanoparticles with an appropriate organic coating in a liquid crystal matrix can enhance the external electric field sensitivity and temperature stability of the examined photonic liquid crystal fibers.

1. Introduction

Blue Phase Liquid Crystal (BPLC) is composed of liquid-crystalline molecules with a specific arrangement, creating a self-assembling cubic structures in the two phases BP I and BP II (Fig. 1) or occurring as an isotropic-like ‘fog phase’ BP III [1, 2]. All three structurally distinct types of the BPLC appear in order of decreasing temperature from the isotropic to cholesteric phase and naturally exist in a relatively narrow temperature range (~0.1-5.0 K). BPLCs are characterized by outstanding properties such as 3D Bragg reflections, optical isotropy, no need any alignment layers, ultra-fast switching speeds (less than 1 ms), and polarization insensitivity in a macroscopic scale for the wavelengths outside their resonance bands [3, 4]. Currently, BPLCs belong to the most promising materials for perspective applications not only in fast-switching LC displays, but also in advanced photonic structures such as photonic crystal fibers (PCFs) [5, 6]. However, so far only a few papers have focused on studies in the latter field, considering mainly characterization of spectral properties of BPLC-filled PCFs. Moreover, these complex photonic structures still have significant limitations in optical communication such as not fast enough response times as well a necessity to use high driving voltage due to a relatively large cladding diameter of the PCF.

Figure 1: Scheme of molecular ordering in cubic structures corresponding to a unit cell of (a) BP I and (b) BP II. Green molecules mean connected helices in neighboring cylinders, and violet rods correspond to an array of liquid-crystalline disclinations in a unit cell.
2. Discussion

Here, spectral and electro-optical properties of a PCF infiltrated with gold nanoparticles-doped BPLC, named as photonic liquid crystal fibers (PLCFs), are shown. For the studies, the 1912 chiral nematic LC mixture was used. It was specially designed and synthesized in the Institute of Chemistry at the Military University of Technology. The major compositions of the 1912 mixture (85.8% by wt.) are photochemically stable fluorinated oligophenyls with fluorinated cyclohexyl- and bicyclohexylbiphenyls, and two optical active dopants added at an appropriate concentration: biphenyl-4,4-dicarboxylic acid bis-(1-methylheptyl) ester (7.0% by wt.) and [1,1;4,1] terphenyl-4,4-dicarboxylic acid bis-(1-methylheptyl) ester (7.2% by wt.) to induce BP phases. The measured macroscopic parameters of the 1912 chiral nematic LC mixture can be found elsewhere [7].

The PCF used in this work was manufactured at Maria Curie-Skłodowska University (MCSU) in Lublin (Poland), and made of pure silica glass (which refractive index n = 1.4568 at λ = 640 nm) with the inclusion diameter d0 = 2.4 μm, pitch Δ = 5.7 μm, and outer diameter D = 125 μm. The cross-section of the investigated PCF structure is depicted in Fig. 2. It was shown that doping BPLC by gold nanoparticles (Au NPs) with a diameter of 2.2 nm, having an appropriate organic coating, ensures a high degree of interaction with the liquid crystal matrix what consequently leads to an increase in the temperature range for BPs occurrence.

![Figure 2: Cross-section of the investigated PCF structure.](image)

The prepared PLCF samples were studied for different temperatures covering both cubic blue phases, and for various concentrations of Au NPs in the range of 0.1-5.0% by wt. Additionally, two orthogonal linearly polarized light waves, in the presence of an external electric field were carried out in the experiment. Here, the equipotential lines of the electric field were assumed to be parallel to the y-axis of the considered PCF structure (compare Fig. 2). It was shown that the investigated Au NPs in BPLC improve electro-optical parameters of the examined PLCFs, providing the lower threshold voltage and speed up response times. Furthermore, it turns out that a control of the light intensity for specific wavelengths can be obtained. Moreover, a range of wavelengths corresponding to low transmission (photonic bandgap) depends on the input light polarization and can be controlled by an external electric field.

3. Conclusions

To conclude, this work expands our preliminary observations by carrying out studies of optical properties of Au NPs-doped cubic BPLCs infiltrating PCFs. It has been shown that the examined photonic system can provide promising tunable spectral properties, enhancing the external electric field sensitivity and temperature stability. This is due to the presence of Au NPs with an appropriate organic coating in the LC matrix. The obtained results indicate lowering the threshold voltage and increasing the operating temperature range of the investigated photonic system. Finally, it was conclusively demonstrated that PCFs filled with Au NPs-doped BPLCs are very attractive photonic devices with possible use of electro-optical modulation, switching, sensing, as well tunable filter applications, providing better transmission properties due to the existence of optical isotropy in BPLC.

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References


Free space topological surface states at the surface of uncorrugated finite gyrotrropic photonic crystals

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Abstract

We present a square photonic crystal that sustains topological surface states at the free space interface. Band structure and direct scattering simulations demonstrate the topological surface mode unidirectionality and immunity to defects and back-scattering.

1. Introduction

Topological insulators exhibit topologically non-trivial electronic band structure, which features an electronic band gap that causes insulating behavior in the bulk while simultaneously supporting protected, unidirectional transport of electrons along their surface without any back-scattering, mostly unperturbed by local defects and impurities. Analog systems have been constructed in photonic crystals where the same behavior applies for the transport of photons instead of electrons and chiral surface states can be found at the interface between gyrotrropic photonic crystals, a feature that attracts enormous attention over the past years, as it promises to pave the path for the realization of photonic circuits without unwanted back-scattering loss which pose critical constraints in photonic circuit technology [1, 2]. Photonic crystals with proper corrugations have been also shown to sustain non trivial surface states at the free space termination [3, 4, 5, 6]. In this paper we present a rectangular photonic crystal properly engineered to sustain topological surface states at the structures interface with the free space [7].

2. Discussion

We assume a two dimensional infinite photonic crystal made of Yttrium-Iron-Garnet that in the presence of a magnetic field of $B = 1600\text{G}$ presents non-diagonal tensor permeability $\mu = 14\mu_0$ and $\kappa = 12.4\mu_0$ (which enforces the time-reversal-symmetry breaking of the photonic crystal). The permittivity is equal to $\epsilon_r = 15\epsilon_0$. The polarization of the field is $E = E_x$. Figure 1(a) and 1(c) show the the degenerate M-points between bands 2 and 3 for radius $R = 0.11a$ (a) and $R = 0.17a$, split into the the bandgap supporting the topological surface states upon applying the external magnetic field. The Chern numbers indicating the topological invariants of the bands are $C_1 = 0$, the second $C_2 = 1$ and the third by $C_3 = -2$ as presented in Figure 1(b) and 1(d). Figure 2(a) presents the detail of the dispersion diagram calculations of the surface states travelling in the lateral direction in a supercell consisting of a photonic crystal infinite in the lateral and finite in the vertical direction. We observe the emergence of two branches green and red that lie below the lightline and in the band gap above the lightline.
point source radiation couple to the topological mode which spins around the structure anticlockwise as it is immune to the corners (defects) of the photonic crystal structure. In Figure 2(a) we present the data points from the Fourier analysis of the surface fields of Figure 2(d) in comparison with the supercell eigenvalue dispersion analysis. We find excellent agreement between the two approaches of characterizing the topological surface mode dispersion.

Figure 2: (a) Detail if the dispersion diagram of the $x$ travelling modes in the supercell. Dots correspond to the data points from the Fourier analysis of the surface fields in (d). (b) and (c) Distribution of the electric field in the topological eigensolutions. (d) Distribution of the electric field, $E_z$, for a chiral topological surface mode at the boundary of the finite photonic crystal/air interface.

In conclusion we showed the emergence of topological, unidirectional surface states at the interfaces of a finite gyrotropic photonic crystal with free space (vacuum), i.e., without an external photonic crystal to enable chiral surface modes. In our study, we calculated the dispersion properties of the topological surface modes in a supercell and demonstrated the one-way directionality in a truncated photonic crystal square using a dipole source. Finally performed a fourier analysis that perfectly reproduced the dispersion derived form the eigensolutions.

Acknowledgement

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References


Vertical assisted directional-coupler from Silicon-on-Insulator to Silicon Nitride platforms

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Abstract

Silicon (Si) and Silicon Nitride (Si3N4) are two leading materials for the creation of photonic integrated circuits (PICs). The necessity of efficiently couple light between Si- and Si3N4-PICs is becoming more relevant to face crucial applications in various technologic sectors, as high bandwidth optical interconnects and mid-infrared and visible optical sensing. However, the strong refractive index mismatch between Si and Si3N4 leads to challenging coupling between the elements used to carry the light throughout the PIC waveguides (WGs). We propose a solution based on vertical assisted directional-couplers allowing a computational Coupling-Efficiency (CE) up to 82%.

1. Introduction

There has been a great effort to develop efficient coupling schemes between high-performance optoelectronic components and passive WGs and resonators on SOI platforms for fiber to chip coupling [1]. On the other hand, Si3N4, due to its lower refractive index and thermo-optic properties, is less susceptible to wavelength selective components thus attracting increasing interest for photonics applications and leading to the necessity of an efficient coupling scheme between the two CMOS-compatible platforms. In this work, we address the issue by presenting two different CMOS-compatible design solutions based on a vertical assisted directional-coupler. Both coupler optimizations were performed combining the couple mode theory and a Particle Swarm Algorithm (PSO) [2] implemented inside Lumerical FDTD software to seek for the best coupler designs in terms of transferring capability of the mode from the Si- into the Si3N4-WG, leading to high computational CEs, up to 82% in the O-band.

2. Device Design

Figure 1 shows the layout of the two different designs, where configuration A has the grating periodicity in the middle of the two WGs, while configuration B has the grating directly etched inside the Si-WG.

Figure 1: Schematics of the vertical coupler device in both configurations: (a) configuration A, i.e. the grating is between the Si- and the Si3N4-WG; (b) configuration B with the grating etched ‘down into the Si-WG. Either the WGs are embedded into SiO2.

The Si- and the Si3N4-WG widths are expanded with adiabatic tapers from 450nm and 1000nm, respectively, to 12μm in the coupler region fulfilling the phase match condition. The refractive index (n) of the Si was fixed at 3.48, while for the Si3N4 was set at 2.05. The Si-WG has a height of 220nm, while the Si3N4 thickness spans between (300÷500) nm. The entire system is embedded in SiO2 (n=1.44) and a 30nm-thick Au-mirror layer, with n set Palik from the Lumerical FDTD library [3], is deposited on top of configuration B. The duty-cycle (DC) of both designs is fixed at 0.5, with a variable period Λ and a total coupler length L=N·Λ, where N indicates the number of periods. In particular, the etching depth (ED) of configuration B is fixed at 70nm. The devices can be fabricated starting from the 220nm-thick SOIs patterned using electron-beam lithography to create the Si-taper, Fig. 1. For configuration A, a first deposition of Si3N4 can be performed via PECVD and, the grating can be patterned lithographically on it and planerized with PECVD of SiO2 or spin-coating of a
Flowable Oxide (FOx). Then, PECVD of Si$_3$N$_4$ can be performed and either the taper and the WG are then inscribed lithographically. For configuration B, the grating is fabricated exploiting the Si layer and then, PECVD of SiO$_2$ and Si$_3$N$_4$ can be performed and the Si$_3$N$_4$-layer exploited to pattern the taper.

### Results and Discussion

Figure 2 shows the 2D maps of the absolute value of the coupling coefficient $k$, defined as [4], as a function of the Si- to Si$_3$N$_4$-WG distance (D) and the Si$_3$N$_4$-WG thickness for configuration A, panel (a), and configuration B, panel (b), evaluated exploiting the FDTD.

![Figure 2: Absolute value of the coupling coefficient $k$ for the two vertical coupling devices: (a) configuration A; (b) configuration B.](image)

This parameter is calculated for the fundamental TE supermodes of the Si- and Si$_3$N$_4$-WGs, where higher $k$ values leads to a better coupling mechanism, and consequently to shorter devices. Both configurations show $k$ parameters in the same range of $10^4$ m$^{-1}$. Panel (a) suggests a best Si$_3$N$_4$-thickness and D value of 300nm and 150m respectively for configuration A. Moving away from these best values results in a lower cross-section between the two supermodes, which reduces the $k$ coefficient. Panel (b) suggests a best Si$_3$N$_4$-WG thickness of 300nm with an optimum distance in the range of values (0±150) nm. Here, the periodicity is defined inside the Si-WG, with a fixed ED, thus the cross-section is less sensitive to a variation in the distance between the WGs. Nevertheless, increasing both the Si$_3$N$_4$-WG thickness and the distance results in a smaller cross-section of the two supermodes lowering the $k$ values. Then, the 2D maps were used to select a proper limited parameter space about the best D values for both configurations for a Si$_3$N$_4$-thickness of 300nm, and the PSO was exploited to seek for the best coupler designs using the CE, calculated through 2D-FDTD simulations, as a feedback. Table 1 reports the optimized parameters found by the PSO for both configurations. From Fig. 2, a value of $k$=2x10$^4$ and $k$=3x10$^4$, respectively for configuration A and B, can be evaluated for the corresponding optimized D values. As a consequence, configuration A shows a longer interaction length, with respect to configuration B consequence of a smaller $k$ coefficient.

### Table 1: Optimized parameter for configuration A and B

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\Lambda$ (nm)</th>
<th>D (nm)</th>
<th>L (\mu m)</th>
<th>Si$_3$N$_4$-WG Thickness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1313</td>
<td>116</td>
<td>38</td>
<td>300</td>
</tr>
<tr>
<td>B</td>
<td>1550</td>
<td>190</td>
<td>29</td>
<td>300</td>
</tr>
</tbody>
</table>

![Figure 3: 3D simulated CE for both configurations.](image)

In this work, we propose two vertical assisted directional coupler designs, able to couple between the fundamental TE modes of a Si- and Si$_3$N$_4$-WG, with a periodicity either created in between the two WGs, configuration A, or directly inside the Si-WG, configuration B. Through the study of the coupling coefficient $k$ and a customize PSO algorithm, implemented inside a commercial FDTD software, the two designs were optimized reaching a 3D simulated CE at the peak of 70% and 82% for configuration A and B, respectively, in the O-band wavelength interval.

### Conclusions

In this work, we propose two vertical assisted directional coupler designs, able to couple between the fundamental TE modes of a Si- and Si$_3$N$_4$-WG, with a periodicity either created in between the two WGs, configuration A, or directly inside the Si-WG, configuration B. Through the study of the coupling coefficient $k$ and a customize PSO algorithm, implemented inside a commercial FDTD software, the two designs were optimized reaching a 3D simulated CE at the peak of 70% and 82% for configuration A and B, respectively, in the O-band wavelength interval.

### References


Linear and nonlinear effects in metamaterials based on magnonic crystals and semiconductors

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Abstract

We present results of theoretical investigations of propagation of spin waves in heterostructure magnonic crystal - semiconductor wafer. Direct current in semiconductor wafer allows to control of band gap characteristics in such structure. In addition, we observed propagating of soliton-like pulses and electrical control of number and velocity of such pulses.

1. Introduction

Ferromagnetic materials in which spin waves can propagate are important research subject in radiophysics. Spin waves propagate in microwave range, they have low attenuation and can be controlled by external magnetic field. Electrical control spin wave properties is actual problem of microwave electronics, since electrical control is usually more energy efficient and faster [1, 2].

In present work, study of influence of direct current in semiconductor (SC) loaded on a magnonic crystal (MC) on spin waves is carried out. It was previously shown that spin wave can be amplified by current in a GaAs semiconductor [3]. In addition, a theoretical study of periodic structures with a semiconductor was carried out [4]. Currently, research of mutual influence of current in semiconductor and spin waves in films of Ittrium Iron Garnet (YIG) is conducted with aim of integrating spin-wave components into semiconductor devices [5]. Investigations of nonlinear effects in such structures were also carried out, and possibility of formation of bright Nonlinear Schrodinger Equation solitons was shown theoretically [6].

We present the results of study of direct current control of position of Bragg band gaps in spectrum of spin waves propagating in heterostructure magnonic crystal - semiconductor (MC/SC). In addition, we investigated gap solitons propagation [7] and possibility of electrical control of number and velocity of such solitons.

2. Model and Theory

We investigated magnonic crystal (MC) based on ferromagnetic film with periodic system of grooves. MC is loaded on the semi-infinite semiconductor plate (SC) (see Fig. 1). The structure is infinite in the $x$, $z$ plane. The external magnetic field $\vec{H}_0$ is directed along the $z$-axis, so that the magnetostatic surface waves (MSSW) propagates along the $x$-axis in this structure. For numerical calculations we obtain dispersion relation from magnetization motion equation in case of magnetostatic surface wave (MSSW):

$$\frac{\partial^2 m}{\partial t^2} = -\omega_m^2 m + \frac{S}{(1 - jY_s)} (\omega_M (1 + jY_s) (S \frac{\partial}{\partial t} + j\omega_H) + j\omega_M^2 Y_s) \frac{\partial m}{\partial x}$$

(1)

where $j$ is the imaginary unit, $m = m_x/M_0$ is the normalized high-frequency component of magnetization, $m_x$ - $x$-projection of high-frequency component of magnetization, $S = 1$ (the - sign refers to the wave propagating in the positive $x$-direction, + in the negative $x$-direction), $\omega_M^2 = \omega_H (\omega_M + \omega_H), \omega_H = \gamma H_0, \omega_M = 4\pi \gamma M$ (in the linear case longitudinal components of magnetic moments $M = M_0), \gamma$ is the gyromagnetic ratio, $H_0$ is the external magnetic field, $d$ is the effective thickness of the ferromagnetic film, the surface conductivity of the MC/SC interface is

$$Y_s = j \sqrt{1 + \frac{\mu_0 \sigma}{k^2}} (\omega - kv),$$

(2)

where $\mu_0$ is the vacuum magnetic permeability, $\sigma$ is the SC conductivity, $v_0 = \mu E$ is the velocity of charge carriers (in the case of Si the electrons), $\mu$ is the mobility of charge carriers, $E$ - magnitude of the electric field applied to the SC layer.

To obtain dispersion relation for MSSW in the periodic structure, we will take into account that the value $d$ in (1) is the periodic function that depends on the longitudinal coordinate $x$ and has the form [8, 9]:

$$d = d_0 + \delta \cos (\pi/L),$$

(3)

where $d_0 = a - \Delta + \Delta b/L, \delta = \frac{2a}{d_0} \sin (\pi b/L), L$ is the period, $\Delta$ and $b$ are the depth and the width of grooves, $a$ is the height of stacks (the introduced designations are shown in Fig. 1). Thus, equation (1) has periodically varying coefficients. To solve this equation (for $\Delta << d_0$), an approach based on the method of coupled waves is used, which consists in the fact that waves propagating in the direct and reflected directions (wave reflected from spatial inhomogeneities) in a periodic system are considered independently, and the periodic structure provides their coupling. The solution of the wave equation (1) with (3) can
be presented as a sum of spatial harmonics of direct and reflected waves:

\[ m = A \exp[j(\omega t - k_0 x)] + B \exp[j(\omega t + k_{-1} x)], \quad (4) \]

where \( A \) and \( B \) are slowly changing complex amplitudes of envelopes of direct and reflected waves, \( \omega = 2\pi f \) is the frequency of input signal (the operating frequency).

Writing the wave equations for these waves and equating the determinant of the resulting set of equations to zero, we obtained the dispersion equation for MSSW in the structure under consideration in the form:

\[ \begin{align*}
-\omega^2 + \omega_M^2 + D_0 k d_0 & \left(-\omega^2 + \omega_M^2 + D_{-1} k_{-1} d_0\right) = 0, \\
D_0 - k \cdot k_{-1} \delta^2, & \quad (5)
\end{align*} \]

where \( D_{0,-1} = \frac{1}{\sqrt{-j \omega_M}} (-j Y_s \omega_M^2 + \omega_M (\omega + \omega_M) (1 + j Y_s)), \) \( k \) is the propagation constant of the zero harmonic of the direct wave, \( k_{-1} \) refers to the minus first harmonic of the reflected wave. The quantities \( k \) and \( k_{-1} \) are coupled by the Bragg condition: \( k_{-1} = -k + 2k_B \) where \( k_B = \pi/L \) is the Bragg propagation constant.

Nonlinear processes in ferromagnetics are caused by the decrease of the effective saturation magnetization with the increase of the amplitude of magnetization dynamics. Thus, taking into account Kerr-type nonlinearity, a longitudinal component of magnetic moments can be presented as [10]:

\[ M \approx M_0 (1 - q |m|^2) \quad (6) \]

where \( q = \frac{1}{2} \left(1 + \frac{|\omega_M^2}{\omega^2} \right) \) is the nonlinearity parameter.

Substituting (3), (4), (6) into equation (1) with neglecting the products of nonlinear terms by the space derivatives we get the set of equations for envelope amplitudes in the form:

\[\begin{align*}
j \left( \frac{\partial A}{\partial t} + V_0 \frac{\partial A}{\partial y} \right) + \eta_0 A + \kappa_0 B + \\
+ \beta_0 (|A|^2 + 2|B|^2) A = 0, \\
j \left( \frac{\partial B}{\partial t} - V_{-1} \frac{\partial B}{\partial y} \right) + \eta_{-1} B + \kappa_{-1} A + \\
+ \beta_{-1} (|B|^2 + 2|A|^2) B = 0,
\end{align*}\]

where \( V_0, \eta_0 = 1, \beta_0 = \frac{D_0}{L} \) is the group velocity, \( \kappa_{0,-1} = \delta V_0 (1 + j Y_s) \) is the periodicity parameter, \( \beta_{0,-1} = \frac{D_0}{L} \) is the nonlinearity coefficient, and \( \eta_{0,-1} = \frac{j \omega^2 - k_B^2 \delta k_{0,-1}}{2}\omega \) is the frequency detuning. Equation (2) is a nonlinear coupled wave equation and describes the dynamics of the MSSW envelopes in the MC/SC structure. All coefficients in the equations depend on the surface conductivity of the MC/SC interface, which, in turn, is determined by the drift velocity of charge carriers.

### 3. Linear effects

The results of calculating the dispersion dependences Eq.(5) for different values of electrons velocity \( v_0 \) in SC layer are presented in Fig. 2a. This figure shows the dispersion characteristics of the direct and reflected MSSW in the absence of coupling between them. Band gaps for MSSW in MC/SC structure are formed at the intersection of the dispersion characteristics of these types of waves (highlighted in dark ellipses). If drift velocity of electrons is aligned with the direction of the MSSW, an increase in drift velocity shifts the band gap downward in frequency.

At \( v_0 = 0 \), the central frequency of the band gap corresponds to the intersection point of the blue curves and is equal to \( \omega_1 \). The band gap in a single MC is formed at \( k_B = \pi/L \). In the MC/SC structure, the band gap is formed for wave numbers different from the Bragg wave number at \( k = k_B \neq k_B \). This phenomenon can be explained by the non-reciprocity of MSSW in the studied structure. For the MSSW propagating in the \( y \) = 0 plane in the forward direction, the distribution of the magnetic potential is concentrated at the interface between the ferromagnetic film and the SC, respectively, this wave is more sensitive to the conductivity of the SC. The formation of the band gaps at a wave number different from the Bragg wave number was previously considered in magnonic crystals with metallization [1]. As shown in Fig. 2a, an increase in the drift velocity does not affect the behaviour of the dispersion characteristics of the reflected waves, but affects the behaviour of the dispersion characteristics of only direct waves propagating along the MC surface adjacent to the SC layer. If the drift velocity is co-directed with the direction of the MSSW \( (v_0 > 0) \), an increase in the drift velocity leads to a shift of the band gap downward in frequency by amount of \( \Delta \omega \). If the drift velocity is counter-directed with the direction of the MSSW \( (v_0 < 0) \), a drift of charges does not affect the position of the band gap.
Among nonlinear effects in MC/SC, we investigated the formation of gap solitons [7]. Such solitons are formed during propagation in periodic structures at Bragg bandgap frequencies. One of the main properties of such solitons is that their speed is less than speed of wave propagation in uniform ferromagnetic film.

The equations (2) were solved numerically under the following initial and boundary conditions: \( A(0) = B(0) = B(l, t) = 0 \), \( A(0, t) = A_0 f(t) \) where \( A_0 \) is the amplitude of the input pulse, the function \( f(t) \) determines the shape of the input rectangular pulse (shown by the dashed curve in Fig. 3, \( l \) is the length of the structure. Let us introduce the transmittance of the MC/SC structure in the following form: \( T = \int_0^{t_{max}} |A(l, t)|^2 dt / \int_0^t |A(0, t)|^2 dt \), where \( t_{max} \) is the observation time.

The inset to Fig. 3 shows the dependence of the transmission coefficient on the signal frequency for three different cases: the linear case in the absence of drift of charges (\(|A_0|^2 = 1 \cdot 10^{-4}, v_0 = 0\)), the nonlinear case in the absence of drift of charges (\(|A_0|^2 = 1.6 \cdot 10^{-3}, v_0 = 0\)), and the nonlinear case in the presence of charge carrier drift (\(|A_0|^2 = 1.6 \cdot 10^{-3}, v_0 = 1.7 \cdot 10^5 \text{ cm/s}\)). In the linear case, with a small amplitude of the input signal in the absence of drift of charges, the central frequency is BG \( f_{lin} \) (black curve). With an increase in the input amplitude, there is a nonlinear shift of the BG to the low-frequency region (green curve). The central frequency of the BG, in this case, is \( f_{nl} \). Note that the effect of a nonlinear BG shift has been theoretically described for spin waves in single and coupled MCs without an SC layer. With a further increase in the velocity of drift of charges, the BG also shifts downward in frequency (red curve). The central frequency of the BG, in this case, is \( f_{fU} \).

If the frequency of the input signal lies near the center frequency of the BG, we can assume \( k_0 = k_{-1} \), and then \( V_0, \kappa_{0, -1} = \kappa, \beta_{0, -1} = \beta, \gamma_{0, -1} = \eta \). Let us choose the frequency of the input signal \( f_0 \) higher than the center frequency of the BG for the chosen power of the input signal, for example, lying in the center of the BG in the linear case \((f_0 = f_{lin}, f_0 > f_{nl})\). In this case, in the set of equations (2) we have \( \eta \approx \omega_{BG} - \omega < 0 \), the detuning of the signal frequency from the central frequency of the BG at a given value of the drift velocity.

Let us consider the features of the propagation of pulses depending on the velocity of drift of charges in the SC based on the numerical solution of equations (2). Fig. 3 shows the shapes of the input pulse (dashed curve) and the shape of the output pulse at different values of the drift velocity (solid curves). At the input signal amplitude \(|A_0|^2 = 1 \cdot 10^{-4} \) and \( v_0 = 0 \) (red curve) the gap soliton (GS) is formed in the output signal between splashes 1 and 2 (these splashes correspond to leading and trailing edges of a rectangular pulse). It can be seen that with an increase in the drift velocity \((v_0 = 1.3 \cdot 10^5 \text{ cm/s})\), the GS approaches the splash 1 of the output signal, i.e., its velocity increases. With a further increase in the drift velocity \((v_0 = 1.7 \cdot 10^5 \text{ cm/s})\), the number of GSs increases. The main role, in this case, is played by an increase in the detuning of the central frequency of the BG.
Figure 3: Time profiles of the input pulse (dashed curve) and output pulses at $x = l$ (solid curves) at different charges.

The inset shows the dependence of the transmission coefficient $T$ on the frequency of the input signal $|A_0|^2 = 1 \cdot 10^{-4}$ and $v_0 = 0$ (black curve), $|A_0|^2 = 1.6 \cdot 10^{-3}$ and $v_0 = 0$ (green curve), $|A_0|^2 = 1.5 \cdot 10^{-3}$ and $v_0 = 1.7 \cdot 10^5 \text{cm/s}$ (red curve).

from the frequency of the input signal $|n|$ with increasing drift velocity. The influence of changes in the group velocity, periodicity and nonlinearity coefficients when changing the drift velocity, in this case, is insignificant. With a further increase in the drift velocity ($v_0 = 2.7 \cdot 10^5 \text{cm/s}$, blue curve), the output pulse has a rectangular shape, i.e., passes without distortion and no GS is formed. This effect is explained by the fact that, at a given value of the drift velocity, the BG shifts downward in frequency (see the red curve in the inset to Fig. 3), and the frequency of the input signal $f_0$ turns out to be outside the BG.

5. Conclusions

Thus, in this work, on the basis of theoretical studies, the possibility of electrical control of band gap characteristics in the MC/SC structure is revealed. A method for electrical control of the parameters of solitons, in particular, the number of pulses and their speed using a current in a semiconductor, has been revealed. The results obtained in this work allow us to consider periodic heterostructures based on MC and SC layers as promising candidates for the integration of magnon elements in a semiconductor architecture. Investigation of nonlinear effects of soliton formation is important in telecommunication applications for compressing pulses and increasing data bitrate.

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References

Modeling and computational techniques
Simulation of Large Metasurfaces through Transfer Function Mask

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Abstract

A more efficient and accurate approach is demonstrated to simulate metasurfaces compared with the FD-BPM approach reported at META2019[1]. The new approach employs FFT-BPM to propagate the transmitted field through a transfer function mask (TFM), which is formed by using rigorous FDTD or RCWA algorithm on local nano-cells. Larger grid and step sizes can be used and the new approach is more efficient and requires less RAM, hence it can be applied to larger metasurfaces. Validations against FDTD and FD-BPM shows it remains accurate, within a reasonable approximation.

1. Introduction

To overcome the inefficiency of rigorous FDTD (Finite-Difference Time-Domain), we have demonstrated at META2019 that BPM (Beam Propagation Method) is an effective alternative to simulate metalenses and metasurfaces[1]. Compared with FDTD, BPM is much more efficient, yet maintains reasonable accuracy. However, for extremely large metasurfaces, it still needs a long time to run and a lot of RAM. Furthermore, BPM is a one-way propagator and cannot account for any backward reflection from the metasurface or resonance inside the nano-cells. To address these shortcomings, we proposed the transfer function mask (TFM) approach, in which the transfer function of each nano-cell is calculated by rigorous FDTD or RCWA and a TFM file T(x_i,y_j) is generated for the designed metasurface. For any given input F_0(x_i,y_j,z_0), the transmitted field F(x_i,y_j,z_0) immediately after the metasurface will be:

F(x_i,y_j,z_0) = T(x_i,y_j) F_0(x_i,y_j,z_0)

Hence, the transmitted field is related to the transfer function of the local nano-cell, but without the impact of coupling from neighboring nano-cells. The propagating field at any position after the metasurface can be calculated by FFT-BPM, which is exact in free space. Because no nano-structures are present in free space, relatively large mesh sizes can be used. According to Nyquist-Shannon sampling theorem, accuracy can be preserved as long as the mesh size is less than half wavelength. Furthermore, the accuracy is independent of propagation step size. Therefore, the FFT-BPM can be much more efficient than the FD-BPM.

2. Validation on a small structure

The validation example we chose is one of those used in previous paper, i.e., diameter D=20µm, numerical aperture NA=0.5, and theoretical focal length F=17.3µm at wavelength λ=532nm. That is the largest structure FDTD can run on our desktop computers, due to the amount of RAM that is required. Shown below in Fig 1 is the comparison between different methods using commercial products from RSoft; FullWAVE (FDTD) and BeamPROP (BPM)[2]. As observed, FFT-BPM through TFM gives results that are very close to FDTD and both are close to the theoretical result, F=17.3µm. The field patterns also appear very close to each other, except TFM approach misses high order scattering, as expected. FD-BPM propagation through the metasurface can catch some of this, but misses some wide-angle scattering, due to the paraxial limitation.

Fig 1: Comparison among different approaches
(a) FDTD: F=16.9µm (b) FFT-BPM: F=17.1µm (c) BPM: F=16.3µm

Fig 2: Phase profiles of the lens at different wavelengths
(a) Blue λ=470nm (b) Green λ=532nm (c) Red λ=650nm

Above simulations were done at designed wavelength with desired unwrapped phase profile for an ideal lens, as shown in Fig 2(b). Because of the dispersion, the phase profiles at wavelengths for blue and red, are not smooth curves as
shown in Fig. 2(a) and 2(c), respectively. These phase discontinuities cause diffraction as observed later. Since the lens is chromatic, the focal length will be different at other wavelengths. Shown below in Fig. 3 and 4 are the simulation results at wavelength $\lambda=470$nm and $\lambda=650$nm for the three different approaches, respectively.

**Fig. 3:** Different simulation results at blue light $\lambda=470$nm

**Fig. 4:** Different simulation results at red light $\lambda=650$nm

As observed, FFT-BPM through TFM files gives closer results to FDTD than does FD-BPM through the nano-structures, due to neglect of reflection and resonance within the nano-structures at those wavelengths.

### 3. Validation on a big structure

For the test on a big metalens with diameter $D=100$µm, we will focus on the comparison between FFT-BPM and FD-BPM since FDTD simulation is simply impossible on a standard desktop. The lens is designed with focal length $F=200$µm at $\lambda=532$nm. Shown in Fig. 5 on the upper is the FFT-BPM result with calculated focal length $F=200.5$µm. The FD-BPM result is shown in the lower figure and the calculated focal length is $F=198$µm.

**Fig. 5:** Simulation results at wavelength $\lambda=532$nm

The performance of this lens at other wavelengths is also tested and the simulation results are shown in Fig. 6 and Fig. 7 for blue ($\lambda=470$nm) and red ($\lambda=650$nm) light. As observed, both methods predicted similar focal lengths and produced similar field patterns. However, the computation time of the FFT-BPM is $1000+ \times$ faster than the FD-BPM. For this particular example, FFT-BPM through TFM takes 7 seconds with $0.24$µmX$0.24$µmX$1$µm mesh, while FD-BPM through nano-structure takes about 2 hours with $0.05$µmX$0.05$µmX$0.1$µm.

**Fig. 6:** Simulation results at wavelength $\lambda=470$nm

**Fig. 7:** Simulation results at wavelength $\lambda=650$nm

### 4. Conclusions

In summary, we have proposed a highly efficient approach to simulate metalenses/metasurfaces by propagating an input field through a TFM using FFT-BPM. The validations show it produces similar results to the more rigorous FDTD method and another efficient FD-BPM. It is several orders of magnitude faster than the FD-BPM approach and can be used for practical design of extremely larger structures.

### References


Electromagnetic Modeling of Finite Fragments of Metamaterials and Metasurfaces based on Method of Minimal Autonomous Blocks

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Abstract
Technique to calculate electromagnetic properties of finite fragments of frequency-selective screens, metasurfaces and flat layers of metamaterials based on method of minimal autonomous blocks is proposed. Use of multichannel macroblocks corresponding to the unit cells of the material and surrounding space, and scattering matrices characterizing them is the basis of the technique. Application of the described technique significantly decreases requirement to RAM compared to other computational electromagnetics methods. Use of several types of macroblocks allows taking into consideration local defects of the structure. The technique makes it possible to model arbitrary excitation modes of finite structures by local and remote sources. Modeling results of finite fragment of frequency-selective surface with complicated structure of unit cell are given.

1. Introduction
Modeling of actual configuration in which investigated periodic structures (e.g. frequency-selective surfaces and metamaterials) will be installed is preferable over cell with periodic conditions. Therefore computational electromagnetics methods for finite fragments of periodic structures are important [1]. One of ways to describe metamaterials and frequency-selective surfaces is effective material parameters (effective surface parameters in case of frequency-selective surfaces [2]). But effective parameters 1) are calculated with uncertainty (in case of metamaterials); 2) do not allow consideration of significantly inhomogeneous material and boundary effects; 3) are depending on incidence angle of excitation.

2. Method of minimal autonomous blocks
Method of minimal autonomous blocks (MAB, also known as MAD) is frequency-domain method using spatial discretization by rectilinear grid [3]. Each cell of the grid has corresponding minimal autonomous block. Virtual waveguide channels are connected to each side of the block. Only TEM waves can propagate in the channels. Electromagnetic (EM) field inside the block is represented as a sum of these TEM waves. Autonomous block is characterized by a scattering matrix (12 order in 3D case). Unknowns which must be found are complex amplitudes of waves between blocks. Spatial dimension of MAB block can be up to 0.25 of a wavelength.

A way to determine complex amplitudes of waves (and, respectively, solution of a problem) using minimal amount of random-access memory (RAM) is an iterative technique of multiple scatterings on autonomous blocks. In this way, it is necessary to store only scattering matrices of blocks and current approximation of complex amplitudes of waves instead of solving sparse system of linear equations. Additional way to save RAM is possible when a problem has several blocks having the same scattering matrix: only one copy of this matrix need to be stored. Neighboring autonomous blocks can be joined together. During this, virtual channels connecting blocks between each other are eliminated. Formed multichannel macroblock is characterized by the scattering matrix computed on the basis of scattering matrices of joined blocks using recomposition algorithm [3]. Multichannel block and its scattering matrix can be used in the iterative technique of multiple scatterings. As result, complex amplitudes of channel waves (i.e., tangential electromagnetic field) only at boundaries of multichannel macroblock are determined. Memory to store complex amplitudes of channel waves inside the multichannel macroblock is not required.

3. Technique to compute finite fragments of metamaterials and metasurfaces
Problem of EM computation of finite fragments of frequency-selective surfaces (including metasurfaces) and flat layers of metamaterials is characterized by big number of the equal complex unit cells. Big amount of RAM and CPU time is required to solve the problem. Proposed technique: 1) Build spatial grid of the problem and select repeating spatial regions with the same structure (e.g.: all types of the structure unit cells; free space regions; surrounding objects); Each selected region with its spatial discretization is treated as macroblock; 2) Compute scattering matrices of the selected macroblocks; 3) Solve the problem by the technique of multiple scatterings (see Section 2); 4) If required, compute the EM field distribution
inside the selected multichannel macroblocks (see Section 2).
Estimation of decrease of RAM requirement is presented for the simple case of equal cubic blocks and cubic computational domain. There are \(N\times N\times N\) minimal autonomous blocks (spatial cells) in the computational domain. Each multichannel macroblock has \(K\times K\times K\) of minimal autonomous blocks. Scattering matrix of multichannel macroblock contains \(P=(K^3(6\text{ sides})(2\text{ polarizations for one channel}))^3=144K^3\) elements. Number of complex numbers required to store complex amplitudes of channel waves for multichannel macroblocks is equal to \(B=(N/K)^3\sqrt{F}\times(2, \text{ because it is necessary to store complex amplitudes of incident and reflected waves})=24N^3/K.\)

Each scattering matrix of multichannel macroblock requires big amount of RAM storage, but decrease of RAM usage is achieved due to the following: a) only one copy of scattering matrix is necessary to store for all identical multichannel macroblocks; b) only complex amplitudes of channel waves at boundaries of multichannel macroblocks must be stored; 2) All resonance effects of a multichannel macroblock are accounted for by its scattering matrix, and that leads to decrease of CPU time required for calculation; 3) No effective parameters are introduced, the problem is solved directly, and the technique is applicable for arbitrary rectangular unit cells including cases when metallic elements of neighboring unit cells are touching each other.

4. Example of calculation using described technique
Finite fragment of a frequency-selective surface (FSS) described in [4] (Fig. 1, a; dimensions \(h_1\) and \(h_3\) are swapped in table II of [4] by mistake) was used as test example. Given FSS was designated to filter harmonics up to 27 GHz for a signal with 3 GHz frequency. Finite fragment of FSS (16x16 unit cells, 83.2x83.2x3.7 mm) placed inside aperture of flat metallic screen is considered. Dimensions of the computational domain: 385x385x2495 mm with simplest absorbing boundaries. Distribution of EM field at 3.1 GHz behind the screen in case of plane wave normal incidence (electric field has amplitude 1 V/m and directed along \(y\) axis) must be found.

Scattering matrices for multichannel macroblocks of FSS, metallic screen and free space were computed. FSS unit cell (Fig. 1, a) was discretized into 21x21x30 block; connection of channels to 2D block with given reflection factor of metal was used to account for metallic foil [3]. Problem was decomposed in 45x45x11 multichannel macroblocks. Time to solve the problem with processor Intel Core I7 6700 is about 5 hours. Used amount of RAM is 2.26 GB. Number of minimal autonomous blocks (cells of the spatial grid) is 494x494x77=18 790 772. Use of iterative algorithm of multiple scatterings without using macroblocks would require 18 790 772x6x2x2x(16 bytes to store a complex number)= 6.72 GB. Note that given problem will require large amount of RAM when trying to set and solve sparse system of linear equations even in case of using iterative algorithms to solve it, because in this case, it is necessary to store elements of scattering matrix of every minimal autonomous block.

Resulting distribution of electric field x-component is shown in Fig. 1, b (the field is calculated at boundaries of multichannel macroblocks; points at which the field is calculated are shown in subfigure of Fig. 1, b).

![Figure 1: a) Modeled unit cell of the FSS (transparency is used to simplify visualization); b) Distribution of electric field calculated according to described technique.](image)

5. Conclusion
The technique based on the MAB method and allowing calculation of electromagnetic properties for finite fragments of frequency-selective surfaces and flat layers of metamaterials is presented. Computational efficiency of the technique is demonstrated for case of frequency-selective surface. Decrease of required RAM is 3 times.
Technique described in the paper can be used for computing problems of topological photonics. Restrictions of the technique: unit cells of periodic structure must have rectangular shape.

References
Analysis of Overcoming Independent Core Light Propagation in Multicore Photonic Crystal fibers with Non-identical Cores Coupling

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Abstract
Multicore photonic crystal fibers with non-identical cores are analyzed numerically using Comsol Multiphysics software. Anisotropy in all cores diameters of multicore photonic crystal fibers leads to different coupling behavior. Such anisotropy causes suppressed the coupling between the core modes at some wavelengths. Then the core modes become uncoupled, and this leads to the light mode propagate independently of their neighbors, by increasing the wavelengths, possibly overcoming this problem. These properties could be a novel candidate for multiplexer and demultiplexer applications.

1. Introduction
Recently, developments have revealed that multicore photonic crystal fiber (MCPCF), which has attracted interest from researchers for the flexibility of its design, uncomplicated manufacturing process [1]. And many research interests are shown towards MCPCF, such as couplers [1, 2], splitter [3], and multiplexer-demultiplexer MUX-DEMUX [4]. Generally, one can happen the difference between the diameters of the cores of MCPCF and become non-identical; this leads to unequal power distribution in each core. In our study, we have numerically investigated the possibility of designing to overcome on the decoupler. And suppression between mode cores in non-identical MCPCF structure.

2. Theory and Design methodology
We start our analysis by designing a seven-core as MCPCF system, see Fig. 1. We suppose that the propagation constant of each core is \( \beta_0 \), the coupling coefficient between different cores is \( \kappa_{0n} \) and \( U_0 \) is the local modal field amplitude in the MCPCF coupled system, can describe as [4, 5]:

\[
i \frac{dU_0}{dz} + \beta_0 U_0 + \kappa_{0n} \sum_{n=1}^N U_n = 0 \quad (1)
\]

By entering a gauge, transformation \( U_n = u_n \exp(i\beta_n z) \) is the eigenvalue equation. The coupling coefficients \( \kappa_{0n} \) between the mode 0 and \( n \), when the diameter of the neighbor cores are changed relative to the central core diameter that represents as (0), can describe in Equation (2).

\[
\kappa_{0n} = (2\Delta_n)^{1/2} \frac{U_0 U_n}{R_n \bar{W}_0} \times \frac{K_0(W_n D_{0n} / R_0)}{K_1(W_n) K_1(W_0)} + \frac{\bar{W}_0 K_0(W_n) I_0(\bar{W}_0) + \bar{W}_0 K_1(W_n) I_0(\bar{W}_0)}{\bar{W}_0^2 + u_n^2}, \quad (2)
\]

3. Discussion
To illustrate our method by introducing anisotropy in all seven-core diameters, such as 3.2um, 3.47um, 3.48um, 3.49um, 3.5um, 3.51um and 3.52um. The structural parameters are the hole diameter \( d \geq 4.8 \mu m \); the pitch is \( a=5.6 \mu m \), core separation \( D=2 \lambda \), and the refractive indices for core and cladding 1.45and 1.4, respectively, see Fig. 2. (a) at the wavelength 1.064um and When increasing the wavelength to 1.55um, see Fig. 2. (b). The results showed that the anisotropy in cores diameters, leads to a small mode mismatch, and in turn, impedes the coupling between these cores, the cores become independent of light propagation of their neighbors. Increasing the wavelength to 1.55um, we found that the coupling efficiency improves, where the coupling occurs between two cores with a little penetration to other cores. Otherwise, each core remains independent of its neighboring.
4. Conclusions

The significant effect of anisotropy in all core diameters of MCPCF is a mode mismatch, which in turn, impedes the coupling between these cores, such that the cores become independent of their neighbors. By increasing the wavelength, it is possible to overcome the problem of suppression of coupling between cores, even if all cores with different diameters; these results may be useful in applications, such as multiplexing, and demultiplexing.

Figure 1: Cross-section of seven-core PCF with five-ring hexagonal lattice modeled using COMSOL MULTIPHYSICS software-based finite element method

Figure 2: Distributions of the unique power for the seven-core with different wavelengths, such as 1.064μm (a) and 1.55μm (b).

References


Bound states in the continuum in asymmetric waveguides: role of proportionate coupling

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Abstract

We perform theoretical analysis of bound states in the continuum (BIC) formation in a resonator coupled to two waveguides. Analytical description provides clues on BIC conditions – a single point in the parameter space, when exact numerical calculations become cumbersome. The Friedrich-Wintgen mechanism can be realized in asymmetric system with proportionate couplings to waveguides. The derived conditions are universal and can be implemented to electronic or electromagnetic waveguides. As an example we present BIC in an asymmetric quantum billiard.

1. Introduction

Typically, a closed system with stationary modes turns into open with leaking modes when the tunneling into channels with continuous spectrum is introduced. However, some states with energy (frequency) lying within the continuous spectrum can be effectively decoupled from it for different reasons. Such states are called bound states in the continuum (BIC), and they were proposed in the eve of quantum mechanics as a kind of a mathematical trick. Today BICs are revealed as a widespread phenomenon of wave nature possessing intriguing physical properties [1, 2].

Among mechanisms of BIC formation, the Friedrich-Wintgen model [3] should be highlighted as it allows a consistent general description requiring neither symmetry of the system (like symmetry-protected BICs), nor specific resonant conditions (Fabry–Perot BICs) [2]. In the present work, we extend it to a resonator with two waveguides attached (closed system interacting with two continua) and show that the condition of proportionate coupling for the BIC formation naturally arises in this case.

2. Analytical treatment

Consider a closed resonator attached to two waveguides (left and right for definiteness) with a single propagating channel in each one. Suppose that there are two levels of the isolated resonator with close energies (frequencies) $\varepsilon_1$ and $\varepsilon_2$. Transmission coefficient can be written in the following general form [4]:

$$T(E) = \frac{|P(E)|^2}{|P(E)|^2 + |Q(E)|^2}. \quad (1)$$

Equation (1) provides a unified description of the interference phenomena: real roots of $P(E)$ correspond to transmission zeroes, real roots of $Q(E)$ – to unity transmission resonances, and common real roots of $P(E)$ and $Q(E)$ indicate BIC formation [4].

In the vicinity of $\varepsilon_1$ and $\varepsilon_2$ functions $P(E)$ and $Q(E)$ in Eq. (1) can be approximated by square polynomials if one takes the contributions from all the rest resonator eigenmodes as constants. Therefore, BIC formation implies that resultant of these polynomials vanishes. We show that for crossing of $\varepsilon_1$ and $\varepsilon_2$ this condition requires:

$$\varepsilon_1 = \varepsilon_2, \quad (2)$$

$$\gamma_1^L = \gamma_2^R, \quad (3)$$

where $\gamma_i^L$ is the coupling between the $i$-th level of the isolated resonator and the left/right waveguide. The energy (frequency) of BIC is then $\varepsilon_{BIC} = \varepsilon_1 = \varepsilon_2$. Condition (2) provides the Friedrich-Wintgen mechanism of BIC formation in the case of coupling to a single continuum [3]. In the case of avoided crossing of $\varepsilon_1$ and $\varepsilon_2$ the condition (3) holds true while the condition (2) for energy (frequency) levels becomes more complicated. Condition of proportionate coupling (3) guarantees that the BIC state will interfere destructively in both directions as soon as Eq. (2) holds true.

It should be noted that conditions (2-3) were derived neglecting the evanescent channels in waveguides. Taking them into account can be done according to the common multi-terminal formalism [5] by adding appropriate self-energies to the effective Hamiltonian of the resonator. For evanescent channels, these self-energies would be purely Hermitian. Therefore, in general, it is difficult to formulate exact conditions for the BIC formation, which would fully take all the transverse modes in electrodes into account. If the influence of evanescent channels is small, then typically BIC formation survives, but conditions (2-3) are slightly modified. Nevertheless, taking all the channels consistently into account is needed to construct the exact amplitude distribution of BIC [1].

3. Numerical calculations

Quantum billiards are well-studied objects in the context of interference phenomena such as BIC [1]. Thus, it is illustrative to consider a 2D square quantum billiard as an
and

\[ L = 10 \text{ nm}, \quad y_L = 1 \text{ eV}, \quad \text{and} \quad y_R = 1 \text{ eV}. \]

We consider the 2D billiard formed by a potential well of 1 eV height with \( h_L = 5 \text{ nm}, \) \( h_R = 4 \text{ nm}, \) \( W = 10 \text{ nm}, \) and \( y_L = 1 \text{ nm}. \) Figure 1b depicts the eigenenergies of the closed resonator with varying \( L. \) Line intersections correspond to the parameters satisfying Eq. (2) exactly. To be specific, we consider degeneracy of states \((1, 3)\) and \((2, 1)\) — point \( A \) \((L = L_A \approx 17.33144 \text{ nm} \) and \( E = E_A \approx 0.18498 \text{ eV})\) and degeneracy of states \((1, 2)\) and \((2, 1)\) — point \( B \) \((L = L_B = 10 \text{ nm} \) and \( E = E_B \approx 0.21082 \text{ eV})\). Here we label states as \((n + 1, m + 1)\), where \( n \) and \( m \) are the numbers of their wavefunctions nodes in \( x \) and \( y \) directions correspondingly. Varying the position of the left waveguide \( y_L \), one modifies matrix elements between the desired states of the isolated resonator and the propagating channel in the left waveguide. The proportionality between couplings \((3)\) is satisfied at \( y_R^A = 1.5871 \text{ nm} \) for the case \( A \) and at \( y_R^B \approx 4.4129 \text{ nm} \) for the case \( B \), and hence BICs are expected in the vicinity of \( L = L_{A,B}, E = E_{A,B}, \) and \( y_R = y_R^{A,B}. \)

Direct numerical calculations show that BICs do exist in this system: for \( L = L_{BIC,A} \approx 17.2696 \text{ nm}, \) \( E = E_{BIC,A} \approx 0.18464215 \text{ eV}, \) and \( y_R = y_{R}^{BIC,A} = 1.5574 \text{ nm}, \) and for \( L = L_{BIC,B} \approx 9.9703 \text{ nm}, \) \( E = E_{BIC,B} \approx 0.20961988 \text{ eV}, \) and \( y_R = y_{R}^{BIC,B} = 4.44187 \text{ nm}. \) These values are close to the estimated above, which satisfy the conditions \((2-3)\). As we have argued, this difference arises due to the influence of evanescent modes in the waveguides, 40 of which were taken into account to ensure the convergence of calculations. Figures 1c,d show the numerically calculated wavefunctions of the mentioned BICs. Similarly, BIC formation is also demonstrated for an asymmetric optical waveguides with resonator.

### 4. Conclusion

In the present work, we propose that the Friedrich-Wintgen mechanism of BIC formation can take place in a resonator with proportionate couplings to waveguides regardless of its symmetry. As an example, we demonstrate a numerically calculated BIC in an asymmetric 2D quantum billiard.

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### References


A low-dimensional nonlinear eigenproblem for the complete complex bandstructure and microscopic fields of arbitrary two-domain metamaterials

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Abstract
Homogenization theories for plasmonic metamaterials usually start with crude approximations that are valid in certain limits in zero order, such as small frequencies, wave vectors and material fill fraction. We here instead present a rigorous solution to Maxwell’s equations in binary periodic materials employing a combined Green’s-Galerkin procedure to obtain the complex-valued eigenmodes of the material. Our theory can be generalized and remains valid in regimes outside of those accessed by standard approaches.

1. Introduction
As the structuring at nanometer length-scales required for visible-light metamaterials (MMs) is still very challenging, a strong theoretical understanding of how the observed optical responses are achieved from the periodic geometry of the MMs is essential to provide guidance in the targeted template design for desired electromagnetic properties. Thanks to the computing power that is available today, trial and error and machine learning strategies are more feasible than ever as brute-force numerical methods such as finite elements or finite difference software is readily available to facilitate the study of hypothetical MMs without fabrication. In this work, we follow a different pathway, namely to develop a theoretical model that not only gives access to the intrinsic eigenmodes (with complex wavevector) of any binary structured MM at small computational cost but does so in a way that provides a fundamentally more intuitive understanding to guide purposeful MM design.

The Maxwell-Garnett approximation and Bruggeman’s formula are perhaps the most well-established effective medium theories (EMTs), and while extremely powerful due to their simplicity, they suffer from substantial limitations with regard to the wavelength range, metal fill fraction and metal domain geometry \cite{11,12,13}. More sophisticated EMTs are subject to some of these limitations, most notably because the effective material parameters assume a homogeneous medium, where the optical response is effectively fitted to a model described by effective permittivity $\varepsilon_{\text{eff}}$ and permeability $\mu_{\text{eff}}$ tensors \cite{14,15,16}, and sometimes at the cost of increasing complexity chirality and magnetoelectric cross-coupling tensors \cite{17,18}. By design however, EMTs are ill-suited to obtain all the evanescent Bloch modes from a proposed MM structure that are for example probed in scattering experiments or by quantum emitters. More recently, combined approaches using EMT, parameter retrieval and boundary element methods have come the closest at characterizing MMs by their frequency dependent eigenmode wave vectors \cite{19,20}. However, typically, these theories are set up to find a complex frequency as the eigenvalue for a given wave vector.

We propose a method to find the full complex bandstructure of arbitrary 3D periodic binary optical MMs with $\mu = 1$ at moderately long wavelengths by using a combined lattice Green’s function and Galerkin approach that results in a nonlinear eigenproblem (NLEP) of low-dimension whose solutions provide the MM eigenmodes.

2. Discussion
Consider an arbitrary binary 3D periodic MM and denote its unit cell by $\Omega = \Omega_1 \cup \Omega_2$ (where $\Omega_1 \cap \Omega_2 = \emptyset$), such that the respective materials determine the wavelength-dependent permittivity $\varepsilon(r, \omega) = \varepsilon_i(\omega)$ for $r \in \Omega_i$, $i = 1, 2$. Using a monochromatic ansatz, where the vacuum wave number is given by $k_0 := \omega/c$ for a fixed frequency $\omega$ and the vacuum speed of light $c$, such that $\delta_i \rightarrow -\omega$, the macroscopic Maxwell equations yield the following Helmholtz-type wave equation for the electric field $E(r)$,

$$H E(r) = \left[k_0^2 - k^2(r)\right] E(r) = \mathbb{C}(r) ,$$

where $H := k_0^2 + \Delta - \nabla \otimes \nabla$, and $k(r) := \sqrt{\varepsilon(r) k_0^2}$ is constant $k_i := \sqrt{\varepsilon_i k_0^2}$ on $\Omega_i$ and we assign $\Omega$ as the metal domain. As a result, the driving field $C$ has compact support on $\Omega_2$, therefore the differential equation Eq. (1) is homogeneous on $\Omega_1$. By the Floquet-Bloch theorem, we have $E(r) = u(r) \exp\{i\kappa \cdot r\}$ for a Bloch wave vector $\kappa$ and a periodic function $u = \sum G E_G \mu_G (P_G := \exp\{iG \cdot r\})$ with respect to the lattice $A = (a_1, a_2)$, i.e. $G := 2\pi A^{-1} p$, $p \in \mathbb{Z}^3$. The vector space of $C$ can be spanned by polynomial coefficient functions $P_n$, with compact support on $\Omega_2$, which are scaled with the Bloch factor for convenience. For many MMs of interest (simple geometry and long wavelengths $\lambda \gg a$), a small polynomial degree suffices.

Substituting these expansions into Eq. (1) and Galerkin testing transforms it into the low-dimensional NLEP on vector space of polynomial basis function coefficients $c_n$:

$$\sum_{\beta} Q_{\alpha\beta} c_{\beta} = \delta k^2 f_2 \sum_{G,\beta} \chi_{\alpha} G^{-1} H^{-1} \chi_{\beta} c_{\beta} ,$$

where $Q_{\alpha\beta}$ and $c_{\beta}$ are the fundamental basis functions and coefficients, respectively.

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with $\delta k^2 := k_1^2 - k_2^2$, the inverse Helmholtz operator in the plane-wave basis

$$\mathcal{H}^{-1} \equiv \frac{1}{k_1^2 - (\mathbf{k} + \mathbf{G})^2} \left[ \mathbb{I} - \frac{(\mathbf{k} + \mathbf{G}) \otimes (\mathbf{k} + \mathbf{G})}{k_1^2} \right];$$

the inner product matrices $V_2 Q_{\alpha\beta} := (P_{\alpha}, P_{\beta})_2$ and $V_2^2 \rho_{\alpha\beta}(\mathbf{G}) := (P_{\alpha}, p_{\alpha} g_{\alpha})_2 (p_{\beta}, g_{\beta})_2$; and the volume $V_2$, the volume fill fraction $f_2$, and the canonical sesquilinear inner product $(f, g)_2 := \int_{\Omega_2} dV \, f^*(r) g(r)$ of $\Omega_2$.

Note that this NLEP has only dimension $3N$ for the number $N$ of driving current basis functions $P_{\alpha} P_{\alpha}$. For plane-wave illumination of a MM slab, the components of the Bloch wave vector $\mathbf{k}$ parallel to a given termination plane are conserved, so that the complex eigenvalues of Eq. (2) are $\kappa_z$ and the associated eigenvectors are the basis vectors $c_n$ of the driven field $\mathbf{c}$.

We demonstrate the validity and strength of the algorithm, including the exact prediction of the microscopic fields, for a 2D periodic silver nano-wire array, which has been recently fabricated using block co-polymer self-assembly as an in-plane broadband type I hyperbolic optical MM [11] and is schematically depicted in Figure 1.

**References**


A Software for Simulation and Computer Aided Inverse Design of Nanophotonic Metamaterials Based on Periodically Patterned Metasurfaces

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Abstract

A software for simulation and inverse design of micro- and nano-optical devices embedding smooth and periodically patterned layers is described. With this tool, a ~ 100% efficient, silicon (Si) based, photodetector (PD) for a near-infrared (NIR) wavelength is designed, and on this example the topological photonics features are shown.

1. Introduction

Metamaterials (MMs) embed metasurfaces (MSs), an important type of which are periodic-pattern MSs [1]. These are in fact optically-thin gratings. Fourier-Floquet modal method for simulation of gratings was first developed for volume gratings. Extended to surface-relief ones in 1980’s, it was named rigorous coupled-wave analysis (RCWA). Despite the RCWA versatility, strong evidence of its overall numerical instability, and lacking convergence was reported in 1990’s. Since then, RCWA has been recasting to overcome these problems. For programming of a recast RCWA we used MATLAB. The reason for this is that MATLAB’s crucial facilities comprise state-of-art linear algebra and optimization packages; its smart codes are highly programming efficient, and graphics is well-developed including an elegant graphical user interface (GUI) builder.

2. In-house software: mathematical and numerical implementation

In-house recast RCWA includes an: (i) in-layer S-matrix propagation algorithm providing unconditional numerical stability [3]; (ii) Fourier-factorization recast due to line- and zigzag-inverse Laurent rules [4, 3, 5]; (iii) normal-vector method [6]. These items were coded with MATLAB, which laid the foundation of the corresponding true programming prototypes in a High-Tech company, and integrated in a toolbox GRATOR. Fig.1 shows the GRATOR’s architecture, open for a custom user, in which 1D-G and 2D-G sub-blocs run independent codes for simulation 1D and 2D patterned gratings. The objective function for the inverse design can be, depending on an application, an electromagnetic (EM) field derived quantity. GRATOR is being updated due to the MATLAB’s and theory’s updates. An open RCWA code by Stanford group [2] is also worth noting.

3. A MM device example and some results

The device, shown in Fig.2, embeds a SiO₂ bilayer microcavity enclosing a ultrathin, 25nm thick, Si layer, and front Si₃N₄-air and back Si₃N₄-SiO₂ grating on Si₃N₄ layer (GL) MSs wrapping. We designed this MM to absorb at the wavelength \( \lambda_0 = 0.8 \mu m \) all p-polarized light input from backside at normal; the simulated absorption band is ultra-narrow with \( Q' = 5926 \). For \( \lambda_0 \), we visualized and analysed the EM fields \( E, H \) and Poynting vector \( S \). Figs.3 and 4
show the modulus and phase plots, respectively, of the magnetic field phasor $H_y$ (the only nonzero component), both jointly with the S arrow map (quiver). The plots’ range is a MM cutoff within grating-period $\Lambda$ in width and a slice, including the front cavity and substrate in part, Si layer, and back GL, in depth. This design contains no back cavity.

4. Discussion and conclusions

$|H_y|$ in Fig.3 shows three pairs of highly peaked surfaces sharply descending to zero level, i.e., it is strongly confined. Due to the $x$-periodicity, the surfaces’ pairs adjoined to the vertical boundaries can be thought halves of another pair.

![Figure 3: Background – the color map of $|H_y|$; foreground – quiver of S. A full line shows a layers interface; dashed line – a grating groove boundary.](image)

arg($H_y$) in Fig.4 show surfaces’ clusters with transitions from negative values, down to $-\pi$, (blue areas) to positive values, up to $\pi$, (red areas), undergoing via line-like zero-phase domains (white areas), and, most sharply, via short lines of indefinite phase (phase singularity).

The EM power density flow (S quiver) in Figs.3, 4 shows singular patterns around the zero field ($H_y = 0$) points, such as vortexes, saddles and spiral flows [7], with zeroth total topological index. As can be seen from Fig.4, the S vortexes are not tied to either the phase-zero or -singularity points. Careful inspection of the S flow in the Si layer shows that the vortexes enter its small parts in the center and near the vertical boundaries. Between these regions and apart from their closest vicinity, S flows almost completely vertically up and down inside the Si layer. Though its thickness is ultra-small, the multiple back and forth S flow across the layer fuels the 100% NIR peak absorption.

To conclude, we reported the in-house toolbox for rigorous EM simulation and inverse design of micro- and nano-optical devices embedding smooth layers and periodically patterned MSs. We presented the example of ultrathin perfect NIR absorption MM designed with this tool. In this example, we demonstrated the tight confinement of the EM field and singular EM power density flows bearing most topological-photonics peculiarities.

References

Other Micro/Nano fabrication and characterization techniques
Development of a high throughput metalens fabrication process relying on Bosch Deep Reactive Ion Etching and UV Nano Imprint Lithography

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Abstract

Current optical components are often bulky, heavy and expensive - thereby inhibiting the application areas of optical technology. Metasurfaces are highly promising in this respect due to their potential of making optical components small, lightweight and cheap. However, virtually all diffraction limited dielectric metasurface lenses to date rely on slow and expensive direct writing methods. At SINTEF Microsystems and Nanotechnology we are developing industrially relevant Bosch Deep Reactive Ion Etching and UV Nano Imprint Lithography processes for metalens fabrication.

1. Introduction

There is growing interest in applying metasurface concepts to industrial and commercial applications following the numerous high impact publications demonstrating their novel light forming capabilities. An important goal in this respect is to develop techniques that allow for large area patterning with high throughput (as agreed upon in [1, 2, 3]). However, virtually all papers to date on high quality dielectric metalenses have been fabricated using Electron Beam Lithography (EBL) (e.g. [4, 5, 6] to name a few) due to its high resolution. As the research field until now has been interested in proof of concepts, the slow writing speed of EBL has not been an issue. However moving onwards, a number of high throughput techniques have been explored, for instance: Interference lithography [7], plasmonic lithography [8], immersion lithography [9], deep-ultraviolet projection lithography [10], pattern transfer [11], additive manufacturing [12], self-assembly [13], and associated high-throughput roll-to-roll and stepping processes[14].

At SINTEF Microsystems and Nanotechnology we are currently approaching the issue by relying on standard silicon processes which are industrially relevant (and in particular CMOS compatible), by developing UV-Nano Imprint Lithography (UV-NIL) in combination with Bosch Deep Reactive Ion Etching (DRIE) for metasurfaces consisting of high aspect silicon structures. NIL has been proposed as an efficient and cost-effective method capable of patterning over large areas on various substrates [2] and Bosch DRIE is particularly known for its capability of etching high aspect structures (which are necessary for high quality dielectric metalens fabrication).

2. Results

We fabricate diffraction-limited metasurface lenses for \( \lambda = 1.55 \mu m \) as shown in Fig. 1 by using standard UV Nano Imprint Lithography (UV-NIL) patterning of a resist mask with subsequent Continuous and Bosch Deep Reactive Ion Etching (DRIE). A characteristic of Bosch DRIE are the "washboard patterns" that arise on the sidewalls of the Si structure. We show by simulations and optical characterisation that such regular surface patterns that are much smaller than the wavelength can be compensated for in the metasurface design.

A well-known challenge of UV-NIL is the existence of a residual resist film between the patterned resist structures and the silicon substrate. We overcome this issue by varying the viscosity of the resist. Another well-known issue is the complexity involved in ensuring good resist-flow among structures for which the filling factors vary over the patterned surface. To avoid such complications we have fabricated metalenses consisting of rectangular Si pillars (which apply phase to the transmitted field through the geometric...
phase, or Pancharatnam-Berry phase, principle).

Another challenge we encounter is an effect in which the patterned resist pillars become slightly broader at their base (like a "tophat"), which make the resulting dimensions of the Si pillars too large. Our target dimensions were on the order of 280nm \(\times\) 400nm, whereas the structures attained in Fig. 1 are roughly 150nm too large. In order to overcome this issue, we (i) attempted to increase the length of the continuous/unpulsed dry-etch step, (ii) attempted to dramatically increase the depths of the "washboard" DRIE patterns in order to make the effective dimensions smaller, and (iii) we oxidized the structure and then performed an oxide strip in order to reduce the structural dimensions. The results of (ii) and (iii) gave structures close to the target dimensions and were characterized optically. This characterization shows that diffraction limited focusing is achieved.

Acknowledgement

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References


Fabrication and Simulation of Photonic Crystals based on Silicon Nanopillars

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Abstract

In this paper we show successful nanofabrication of photonic crystals based on up to 3 µm long silicon nanopillars. Different nanopillars with 60 to 100 nm radius, a triangular distribution and pitch of 500 nm have been fabricated on silicon or Silicon-On-Insulator substrates. Simulations of the electromagnetic field distribution inside these devices have been carried out to ensure the correct behaviour of the samples as photonic crystals, waveguides and resonators for their use in sensing applications.

1. Introduction

Photonic integrated circuits are devices that connect different photonic elements such as waveguides, ring resonators or photonic crystals (PC) [1]. Because of their prospections to become the photonic based equivalent of integrated electronic systems, many papers can be found dealing with the theoretical and experimental behaviour of photonic integrated devices. However, technological difficulties for the fabrication of devices based on nanopillars, have limited their development and only the simplest configurations have been experimentally reported, disregarding the more complex ones. Furthermore, experimental difficulties in finding the correct working conditions of these nanostructures delayed the full development of these systems.

PC are one of the most powerful elements of integrated circuits for light guiding due to their photonic band gap (PBG). This PBG allows highly efficient waveguiding even for sharp waveguides (WG) bends and junctions. Most of the currently operating systems using PC are based on arrays of holes in dielectric material slabs. In this paper we show the results of our work where we considered the reverse configuration based on silicon pillars in a low refractive index medium, namely water.

2. Simulation

The simulations here presented have been performed using MEEP (https://mEEP.readthedocs.io/), an open-source software package developed at the Massachusetts Institute of Technology (MIT). This package uses the Finite-Difference-Time-Domain (FDTD) method to discretely solve Maxwell’s equations within a finite volume. Due to the interest in applying these devices in liquid environments, in this work the low refractive index material is water instead of the generally used air. This affects the wavelength at which the PBG occurs, as well as the resonance peaks red shift compared to their calculated values in air because of the smaller difference between the background and the pillar’s refractive index [2].

2.1. Photonic crystal

PC simulations using different radius (r) and pitch (a) values have been performed with the aim of selecting the optimal configuration of the PC.

![Figure 1. Gap-to-midgap ratio vs the r/a ratio.](image)

Simulated structures have shown a PBG in the near infrared (NIR) spectral region. Here we report the gap-to-midgap ratio as a figure of merit of the PBG quality. As it is predicted in literature [2], a parabolic tendency is observed,
with a maximum at a radius-to-pitch \((r/a)\) ratio of 0.18 (Fig. 1).

2.2. Waveguides, Y-junctions and cavities

As commented above, WG within a PC have high efficiency in light guiding, even more than in conventional fiber-optic based WG. This fact is due to the almost perfect light confinement in the WG for frequencies in the PBG [3]. In addition, almost any type of bends can be achieved without important loses.

We have simulated different WG to ensure the light propagation through the structures and in the presence of Y-junctions. Finally, we have also studied resonating cavities inside the WG, again, with their resonance frequency lying within the WG. Different simulations have been carried out by placing one or several cavities at different positions inside the WG. In Fig. 2 we show a WG with one cavity in the middle where the radii of the pillars creating the cavity (in green colour in the inset figure) have been changed.

Figure 2. Peak induced by the location of a WG and a cavity in a PC with \(a=500\) nm and \(r=100\) nm. Different radii of the pillars creating the cavity have been considered.

3. Fabrication

We used some of the most advanced silicon nanofabrication technologies inside DTU’s cleanroom facilities for developing our samples. This allowed us to obtain high aspect ratio structures with almost perfect cylindrical shape. Different substrates have been used during our investigation: for the optimization of the process conditions, silicon substrates have been used, while SOI-substrates have been processed with the same conditions to obtain devices suitable for photonic measurements.

The fabrication steps consist on an electron beam lithography (EBL) followed by anisotropic dry etching process using reactive ion etching (RIE). The EBL process flow consists on a first photore sist deposition (AR-P 6200.09), giving rise to a thickness of 180 nm, next exposed by a 100 kV electron beam (JEOL JBX-9500FSZ). The developer AR 600-546 is used for the dissolution of the exposed resist, which is followed by a 20 nm-thick aluminium layer deposited by electron beam evaporation. Finally, a lift-off step using Remover 1165, dissolves the remaining photosist together with the aluminum layer which is on top of it, leaving the aluminium only in the regions where it is in direct contact with the substrate. RIE using SF\(_6\):C\(_3\)F\(_8\) chemistries, performs anisotropic etch of the unprotected silicon. For the SOI process, prior the electron beam exposure a thin (20 nm) aluminium layer is thermal evaporated on the photoresist in order to allow electron discharge during the exposure and is removed with TMAH after the EBL step.

Figure 3. Scanning electron microscope (SEM) images at 30° inclination. The inset shows almost perfect cylindrical shaped pillars with a height of 2.15 \(\mu\)m.

PC with 500 nm pitch and 100 nm pillar’s radii have been fabricated. Furthermore, 60 nm radii pillars have been successfully etched on the same sample inside the WG, as can be seen in Fig. 3, creating WG with cavities in the structure. Next step in the fabrication process on SOI substrates will be to further extend the etching down to the silicon oxide in order to fabricate longitudinal heterostructured pillars. These structures will still behave as photonic crystal, as theoretically predicted elsewhere [4].

4. Conclusions

We have successfully designed, simulated and fabricated PC based on a triangular lattice of silicon pillars with optimized band gaps. The effect of introducing WG and cavities has been also investigated, aiming to exploit the dependence of resonant mode energy with the surrounding media for sensing applications.

Acknowledgements

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References

Effect of deposition angle on fabrication of plasmonic metal nanocones

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Abstract

Metal nanocones can be used to enhance light–matter interactions or for location-specific plasmonic sensing. Their fabrication often utilizes self-shading effect, which occurs during metal film evaporation into circular nanowells. We present a view on the fabrication of ordered arrays of gold nanocones using electron-beam lithography/evaporation. Lateral position of the substrate during the evaporation influences the symmetry of the fabricated nanocones and that off-axis deposition forms asymmetric structures. Our findings help to identify limits for production of wafer-scale arrays.

1. Introduction

Localized surface plasmon resonance of metal nanostructures is a highly studied topic with plenty of applications (heat-assisted magnetic recording, imaging below the diffraction limit, construction of metasurfaces, or biosensing). These applications utilize various shape of nanostructures ranging from simple discs or cuboids in planar geometries to 3D nanostructures having chiral or other sophisticated shapes. This study examines 3D metal nanocones, which offer several unique features like highly accessible hotspots exposed to the environment or different resonant modes connected with different excitation and collection geometries. Metal nanocones also seem like a promising platform for location-specific biosensors, where the two analyte locations (tip or base) can be distinguished as characteristic spectral shifts of the two relevant plasmonic modes [1].

Metal nanocones can be fabricated by several top-down or bottom-up strategies having its natural advantages and weaknesses:
- Focused ion beam (FIB) milling [2] or electron beam induced deposition (EBID) of metals (allow very accurate control of the shape and locations of the nanocones, slow techniques unsuitable for fabrication on large areas).
- Dry etching of metal films through a nanostructured mask (much faster process than FIB and EBID, large areas of nanocones can be produced on planar or even non-planar surfaces [3]).
- Processes based on self-formation of nanocones inside cylindrical nanowell templates during metal deposition using an effect known as self-shading [1] (faster than FIB and EBID usable for large areas of nanocones).

The last-mentioned strategy is generally preferred way, because the nanowells can be prepared by all sorts of lithographic procedures (colloidal lithography, nanoimprint lithography, UV laser interference lithography, or electron beam lithography - EBL) and the self-shading effect works for nanowells made from polymer resist or inorganic dielectrics like SiN. The cone-shaped nanostructures inside the wells during deposition of a metal onto the mask aperture leading to decrease of its effective size (see Fig. 1).

Figure 1: Schema of fabrication process. (a) Resist nanowells with two diameters are fabricated by EBL on the silicon substrate. (b) The gold nanocones are formed inside the nanowells via the self-shading effect during gold evaporation. (c) The free-standing structures on the silicon substrate are created after the lift-off.

Despite the fact that the self-shading effect was used for many times, we want to bring attention to one problematic aspect of the process. Imperfect planar alignment of the substrate during deposition or the inherent multi-directionality of physical vapor deposition methods leads to broken symmetry of the nanocones fabricated on large-scale substrates. These asymmetries are directly related to the position on the sample holder. Our results described here should help to better understand the important aspects of the self-shading mechanism, which plays a role even in the fabrication of simple flat nanodiscs.
2. Fabrication of samples

Silicon substrates were covered with 300 nm of positive tone electron-beam resist (CSAR 62). Hexagonal arrays of circular nanowells with nominal diameters of 50, 100 and 200 nm and various spacings were patterned by EBL using a scanning electron microscope (SEM, MIRA3, Tescan, with a laser interferometer stage RAITH). After the developing procedure, the resist was shortly stripped in O₂ plasma (PlasmaPro NGP 80, Oxford Instruments Ltd.). Samples with the final resist nanowells were mounted onto different lateral positions of the sample holder inside the deposition chamber (see Fig. 2, top) and were then covered by a 5 nm thin titanium adhesion layer and by a 245 nm thick gold film in an ultra-high vacuum electron beam evaporator (Bestec GmbH). The holder perpendicular to the deposition beam and proper deposition rate (2.2 Å/s in our case) are crucial to get the nanocone shape. Finally, the lift-off process was performed in a common CSAR remover.

![Figure 2: The shape of nanocones with 50, 100 and 200-nm diameter in SEM under the top, front and side view (tilt of 55°) together with the schema of deposition geometry and sample arrangement on the evaporator holder with 4-inch wafer (gray circle) in the center.](image)

3. Results and discussions

Our study of the influence of sample position during the deposition showed that the most symmetric nanocone structures were formed on the substrates located at the center of the holder (Fig. 2b). As the total thickness of the deposited metals was 250 nm, nanowells with 200 nm diameter were too wide to get clogged during the deposition and therefore the truncated nanocones were formed. Smaller nanowells with 50 nm and 100 nm diameters ended up with sharp nanocones having the height–diameter aspect ratio close to 2:1. The thickness of the deposited gold film thus, in our case, had to be at least twice as large as the diameter of the nanowell to ensure the production of sharp nanocones.

When the substrates were placed out of the center of the sample holder during the deposition, the shape of the nanocones significantly changed (Fig 2a, c). Off-axis deposition leads to tilted nanocones with asymmetric profile, which can have even a slightly elliptical basis. The whole effect can be ascribed to the imperfect directionality of the deposition, which is conventionally described by Lambert’s cosine law [4]. We tested also the deposition onto substrates placed exactly in the center of the sample holder, but having a slight tilt with respect to the holder surface. The base of the formed nanocones is elliptical and the tip of the nanocone is eccentrically located. All these findings influence also fabrication of planar nanostructures, like plasmonic disc nanoantennas (resemble more truncated nanocones than cylindrical structures).

4. Conclusions

Here we have shown that symmetric metal nanocones can be formed by self-shading effect only when the metal deposition direction is almost perfectly perpendicular to the sample surface. This requirement is very hard to achieve in practice as even a small tilt of the sample or its lateral shift out from the sample holder center will result in deviation from perpendicular deposition in many physical vapor deposition systems. Moreover, the resulting asymmetry is hard to identify in the conventional SEM images acquired under normal incidence. We thus suggest that the deposition results should be well controlled and confirmed using SEM imaging in tilted configuration from more than one side. When large areas of symmetric nanostructures are needed, the inherently asymmetric physical vapor deposition could be compensated by non-planar sample holders.

Acknowledgements

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References


Investigating Plasmon-Induced Field Enhancement, 

Comparative study of monocrystalline and polycrystalline gold plasmonic nanorods

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Abstract

Plasmonic antennas are often fabricated by lithographic patterning of a thin metallic film and its properties are then intimately related to the quality of the resulting structures. Here we compare two kinds of thin gold films: polycrystalline thin film deposited by magnetron sputtering, and chemically synthesized monocrystalline gold platelet. Both metallic substrates were used to fabricate plasmonic nanorods using focused ion beam lithography. The resulting nanorods were characterized by scanning transmission electron microscopy and electron energy loss spectroscopy.

1. Introduction

Plasmonic antennas exhibit rather extraordinary properties stemming from their unmatched ability to concentrate light into the nanoscale volumes. This renders them applicable in many research areas ranging from nano-optics, sensing and medicine, to energy harvesting.

Metallic plasmonic antennas are typically prepared by lithographic techniques – either indirectly by electron beam using electron-sensitive resist, or directly by milling with a focused ion beam (FIB) [1]. Resulting plasmonic antennas then have properties depending on their size, shape, surrounding media and, crucially, antenna material itself. Typical plasmonic antennas are fabricated from thin polycrystalline metallic layers deposited by sputtering or evaporation techniques with randomly oriented grains of varying sizes. This inner structure of gold significantly affects the fabrication resolution and overall shape making each antenna slightly different, which may bring difficulties in single particle studies. This issue can be overcome by utilizing synthesized metallic monocrystalline platelets with a large enough area that whole antenna arrays can be fabricated from the same metallic crystal [2].

Here we show a direct comparison of individual monocrystalline and polycrystalline gold plasmonic rod antennas studied by scanning transmission electron microscopy (STEM) combined with electron energy loss spectroscopy (EELS), with the focus on plasmon resonance parameters as well as visualization of the induced plasmon modes.

Figure 1: (a) Schematic representation of the fabrication procedures utilized for Au antenna fabrication and the actual results after FIB lithography in (b) polycrystalline Au layer and (c) monocrystalline Au platelet with the corresponding electron diffraction patterns shown in the insets.

2. Gold antenna fabrication procedures

Two kinds of gold substrates were prepared on 30 nm thin SiNx TEM membranes using the procedures outlined in Fig. 1(a). Firstly, the membranes with monocrystalline gold were prepared using the modified procedure by Kulkarni [2]. Briefly, the \((\text{AuCl}_4)^-\) ions were phase-transferred from aqueous solution into toluene using tetracetylammonium bromide (TOABr) as a phase transfer agent. Typically, 1 µl of the resulting toluene solution containing \((\text{AuCl}_4)^-\)·TOABr precursor was applied onto a membrane which was then heated to 140-145 °C for about 40 hours. The process resulted in gold monocrystal platelets with lateral sizes in tens of µm and thickness in tens to hundreds of nm while only the thinner ones (below 100 nm) were used for subsequent FIB lithography.

Secondly, the membranes with the polycrystalline gold were prepared conventionally using magnetron sputtering in coater Leica EM ACE600 with nominal thickness of 30 nm without any adhesion layer.
FIB lithography on both kinds of gold substrates was performed on FEI Helios dual-beam system and resulting rod antennas are shown in Fig. 1(b), (c), where monocrystalline gold is milled away much more uniformly. The insets correspond to the selected area electron diffraction patterns of the gold substrates confirming the polycrystalline nature of a sputtered gold layer and monocrystalline nature of the synthesized gold platelet, respectively.

3. Characterization of plasmonic properties

To analyse the plasmonic properties of the fabricated antennas, we utilized FEI Titan TEM microscope equipped with an EELS spectrometer. Detailed images of individual antennas have revealed that monocrystalline antennas have generally smoother edges and they tend to have almost identical shape, when fabricated from the same polycrystalline platelet, as opposed to polycrystalline ones, where each antenna has a different shape. EELS analysis revealed two main modes excited in the rod antennas shown in Fig. 2(a), (b) – longitudinal dipole mode around 1.1 eV and longitudinal quadrupole mode around 1.7 eV [3], followed by undistinguishable higher order modes. The resulting spectra were integrated over the positions highlighted in STEM dark field images shown in Fig. 2(c), (f), where the colors correspond to the spectra in Fig. 2(a), (b). EEL maps show the spatial distribution of the two main modes at the respective peak energies which display the dipole mode in Fig. 2(d), (g) at the lower energy peaks as well as the quadrupole mode in Fig. 2(e), (h) at the higher energy peaks.

Overall, plasmon resonance parameters (e.g. quality factors) of both types of antennas are very similar, with polycrystalline antennas having slightly better defined longitudinal dipole mode, while the quadrupole mode is better defined in monocrystalline antennas which have both modes generally shifted towards higher plasmon energies.

4. Conclusions

In conclusion, we have shown a direct comparison of plasmonic properties of monocrystalline and polycrystalline gold rod antennas using EELS based on two main modes. We have observed comparable quality of the longitudinal dipole mode and only slight improvement in the quadrupole mode for the monocrystalline antennas compared to the polycrystalline ones. Nevertheless, monocrystals allow a fabrication of antennas with significantly smaller deviations in shape and plasmon resonance parameters, when fabricated from single gold platelet. This might be beneficial for applications that require antennas with a narrow distribution of sizes and resulting plasmon resonance parameters.

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References

Temperature effects on the surface plasmon resonance in Bi$_2$O$_3$–Ag eutectic composite

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Abstract

The temperature dependences of spectral position, width and intensity of the surface plasmons of metallic Ag nanoparticles in Bi$_2$O$_3$–Ag were studied in the temperature range from ambient conditions to 500 °C. The increase of temperature leads to nonlinear and appreciable redshift and broadening of the localized surface plasmon resonance band in Bi$_2$O$_3$–Ag. The observed dependences were compared with temperature dependences and simple Drude-Lorentz approximation.

1. Introduction

Nanoplasmonic materials are intensively studied with possible uses in a diverse array of fields such as photonics, optoelectronics, photovoltaics and medicine [1]. A remarkable property of nanoplasmonic materials is their ability to keep the optical energy concentrated on the nanoscale due to modes called surface plasmons (SPs). Recently, eutectic solidification [2] has been proposed as one of the most promising bottom-up methods for manufacturing of metamaterials [3], plasmonic materials [4] and photonic crystals [5]. Eutectic solidification enables crystallization of a two-phase solid, often with an interesting self-organized micro-/nanostructure from a miscible liquid phase at a certain temperature [6]. More recently the plasmonic effect was presented in a eutectic composite for the first time with a Bi$_2$O$_3$–Ag composition [4,7]. After annealing the Bi$_2$O$_3$–Ag eutectic material, metal nanoparticles (NPs): silver and bismuth are formed, which are responsible for the occurrence of localized surface plasmon resonance (LSPR) in the visible wavelength range, at ~595 nm. Using different annealing conditions such as the atmosphere, time and temperature, it is possible to control the peak frequency of the LSPR [7].

Here, we report on the temperature dependences of spectral position, width and intensity of the surface plasmon of metallic Ag NPs in Bi$_2$O$_3$–Ag in the temperature range 25–500 °C. The increase of temperature leads to appreciable redshift and broadening of the LSPR in Bi$_2$O$_3$–Ag eutectic material.

2. Results and Discussion

In the Bi$_2$O$_3$–Ag composite, the Ag phase is consistently distributed as a net of triangular micron-scale precipitates interconnected with Ag nanosheets with lengths of a few/tens micrometres, Figure 1. The triangular precipitates are elongated in the growth direction and their size, as well as the thickness of the nanosheets, mostly depends on the pulling rate.

Figure 1. The microstructure of the Bi$_2$O$_3$–Ag eutectic composite.

After annealing in an air atmosphere, silver diffuses into the Bi$_2$O$_3$ phase and Ag and Bi NPs are formed. This material exhibits LSPR at ~580 nm due to the presence of silver NPs.

The optical absorbance spectra of Bi$_2$O$_3$–Ag samples were performed in the temperature range 25–500 °C using a CARY 20/20 PV microspectrophotometer with Linkam TS1500 temperature-controlled stage. The absorption spectra recorded for various temperatures of the Bi$_2$O$_3$–Ag eutectic are shown in Fig. 2 and Table 1. The LSPR band can be identified as peaks at 583–623 nm depending on the temperature. Moreover, the absorption edge of Bi$_2$O$_3$ matrix is shifted to the longer wavelengths for all the samples.
Figure 2: Absorbance spectra of the Bi$_2$O$_3$-Ag eutectic composite measured at various temperatures. This is the figure caption. Dashed lines show the shift of the absorption edge of Bi$_2$O$_3$ and the LSPR with temperature, respectively.

Table 1: Optical properties of the Bi$_2$O$_3$-Ag eutectic composite at high temperatures

<table>
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<tr>
<th>Temperature (°C)</th>
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The observed temperature induced redshift of the absorption edge of Bi$_2$O$_3$ matrix is due to its bandgap narrowing and follows the empirical Varshni formula which relates variation of the energy gap ($E_g$) with temperature ($T$) in semiconductors [8]. Furthermore, our experiments show the nonlinear redshift of the LSPR as the temperature of the sample increases and finally vanishes at a temperature of 500 °C. This behavior is mostly due to a thermal expansion of metallic NPs resulting in critical reduction of the number of free carriers (below $10^{20}$ 1/cm$^3$). This behaviour can be observed in systems containing small nanoparticles, below over a dozen nanometers in radius (in this system about 3 nm [7]), embedded in dielectric media [9].

3. Conclusions

The temperature-dependent studies on the plasmonic eutectic Bi$_2$O$_3$-Ag composite showed the nonlinear tendency to redshifting both for the absorption edge in host-matrix and guest-plasmonic Ag NPs. There can be several processes behind that nonlinearity, such as the change of: (i) the Ag NPs size and their volume fraction, (ii) carriers concentration in NPs, (iii) the dielectric function of the dielectric matrix $\varepsilon_{\text{m}}$ resulting in modification of the Fröhlich resonance condition or increasing electron-phonon scattering, that requires further studies.

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References

What Influences Surface Plasmon Resonance Linewidth in MIM Structures Obtained by Colloidal Self-Assembly

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Abstract

Localized surface plasmon resonances (LSPRs) have been extensively studied in the past decades, due to their excellent ability to condense the light into nanometric length-scale. However, LSPRs often suffer from spectral broadening, a crucial origin of which is fabrication inaccuracies. Unfortunately, there is yet an efficient way to evaluate this impact, rendering the researchers having to rely on rather intensive, time-consuming trial-and-error experimentations. We present in this talk an approach to evaluate the various fabrication contributors to the spectral broadening phenomenon, providing a possibility of efficient optimization in lieu of extended experiments. This will shed light to automated fabrication and optimization, integrated design and improved \textit{ab initio} modeling.

1. Introduction

Due to the fast development of nanofabrication technologies, on par with the excellent light-confinement ability from the surface plasmons, the field of nanoplasmonics has been vigorously studied and utilized, from fundamental science, to real-life applications. However, a problem remains when narrow linewidth, or high quality-factor (Q-factor) is pursued. Challenges here originate not only from the intrinsic radiative loss from the noble metal material, but also from the fabrication inaccuracies.

Many efforts have been made to seek LSPRs with better performance via delicate structural design. This approach either invokes near-field coupling or constructive far-field coupling. Albeit successful, it is equally important to understand the contributors to the usually broadened spectra we observe experimentally, as compared to their theoretical or simulated counterparts. A number of reasons have been listed, including surface roughness, structural dimension variations, as well as degradation of materials. While all of the reasons mentioned above are plausible, detailing and isolating various factors remains challenging and yet to be fully explored.

In this talk, we will attempt to address this issue with our latest results. We have systematically studied the plasmonic behavior of the classic metal-insulator-metal (MIM) structure and cross-examined a large set of possible common fabrication errors. These errors were separately implemented into the finite-difference time-domain (FDTD) simulations, allowing us to evaluate various factors in a more controlled, isolated fashion, which is impossible experimentally. We believe our findings can be transposed into other similar plasmonic systems, and our evaluation approach can provide an efficient alternative in performance optimization, expediting the future manufacturing of integrated plasmonic devices.

2. Results and discussion

Here we show first a brief conceptual illustration, demonstrating a few possible reasons for spectral discrepancies in between experimental and simulation results. Since isolating these factors are next to impossible to implement experimentally, we resolved to the simulation approach. First, the MIM structure was carefully examined in experiments and the structural dimensions, as well as material optical properties were evaluated. The results were then used to construct the simulation scenarios, to reflect the various contributors including surface roughness, number of defects, as well as deviation in structural parameters, respectively.

Our results successfully disambiguate the aforementioned contributors, namely deviations in structural dimensions, surface roughness, and presence of defects, in how they impact the spectra, respectively. Our results further suggested a surprisingly robust response of the plasmonic
system to fabrication inaccuracies, as shown briefly in Figure 1D and 1E. We will present further details in the talk.

![Image](https://via.placeholder.com/150)

Figure 1: (A) Conceptual illustration, showing the core question that this talk will address, i.e., discussing what are the most prominent origins of simulation-vs-experimental discrepancies. (B) Illustration of the structural design. Here we show a cross-section view of the structure stack, including a full Au mirror at the bottom, SiO₂ insulator, followed by a gold nanohole array on top. (C) A representative SEM image of said nanohole array. (D, E) Evaluation of the impact of defects on the spectral lineshape, as well as spectral shifts.

Acknowledgements

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References


New materials for photonics (Graphene, MoS2, WS2, etc)
Graphene-metal hybrid for strongly enhanced terahertz harmonics

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Abstract
By combining the peculiar ultrafast heating-cooling dynamics of graphene electrons with the enhancement of incident electromagnetic fields by a metallic grating, we have created a hybrid structure with an unprecedentedly large third order (sheet) susceptibility in the terahertz range. In particular, we observe terahertz (THz) third harmonic generation with a field conversion efficiency above 1%. The nonlinear enhancement furthermore allows for the observation of signatures of higher harmonics (up to 9th order) using a table-top laser setup.

1. Introduction
Whereas several excellent materials exist for nonlinear conversion of incident light in the visible and near-infrared range (BBO, LiNbO₃, KTP, KDP, ZnTe, etc.), performing nonlinear optical conversion in the THz range has remained more challenging. Until recently, the highest THz nonlinear (sheet) susceptibilities were achieved in quantum-well systems. However these systems require complex growth strategies in order to achieve atomic lattice matching. With the advent of gapless Dirac materials, this situation has changed drastically, as these materials allow for efficient generation of THz harmonics.

In particular, it was demonstrated very recently that monolayer graphene [1] and the Dirac semimetal Cd₃As₂ [2,3] give rise to highly efficient generation of THz harmonics. In contrast to typical nonlinear optics in other wavelength ranges, THz harmonic generation in graphene is the result of the collective thermal response of the electronic system of graphene. This works as follows: During the interaction with an incident THz wave, the electrons absorb and redistribute the energy from the incident wave, while maintaining a thermal quasi-equilibrium, and follow the (square of the) incident wave with their ultrafast heating-cooling dynamics. Due to the low electronic heat capacity of graphene the electrons heat up significantly: on the order of 1000 K for very moderate incident fields of tens of kV/cm. Then, as a second ingredient, we note that heating of the graphene electronic system leads to a decrease in its THz conductivity, and thus in THz absorption, c.f. [4,5,6]. These ingredients together give rise to a very strong nonlinear susceptibility and efficient generation of THz harmonics in monolayer graphene when excited by multicycle pulses [1].

2. Hybrid graphene-grating system and results
Here we combine monolayer graphene with a metallic micro-grating that provides field enhancement in the gap between the metal bars (see Figure 1). Field enhancement is highly attractive for nonlinear optics, as the enhancement acts in a nonlinear fashion: if the field is enhanced by a factor 2, the intensity of the n-th harmonic is enhanced by a factor 2ⁿ in the nonlinearly active material. In our hybrid graphene-grating system (10% graphene, 90% metal), we achieve field enhancement of a factor ~5, and experimentally observe an overall enhancement of harmonic intensity by 3 orders of magnitude. This was measured using multicycle THz pulses from the TELBE beam facility, a new superconducting radiofrequency accelerator-based super-radiant THz source [7]. We used an incident frequency of 0.7 THz and a field strength ranging from just a few kV/cm to almost 100 kV/cm. Generated signals were measured using electro-optic sampling.

We extract an unprecedentedly large third order susceptibility of χ⁽³⁾ ~10⁻⁸ m²/V², or χ⁽³⁾₂₀ ~10⁻¹⁶ m²/V² when expressed as a two-dimensional sheet value. Even with a field strength of only a few tens of kV/cm, we observe terahertz (THz) third harmonic generation with a field conversion efficiency above 1% and signatures of higher harmonics (up to 9th order). This is remarkable, considering that nonlinear optics typically requires fields in the MV/cm range, even in the visible. These results open avenues for the technological exploitation of
hybrid graphene-grating structures as highly nonlinear THz metamaterial.

Figure 1: Multicycle THz waveform at 0.7 THz (left, measured via electro-optic sampling) incident on a hybrid graphene-grating structure (middle, schematic). When the THz waveform is incident on the metallic grating, field enhancement occurs and significantly more third harmonic intensity (at 2.1 THz) is created (top right, measurement data in red) than without metallic grating (bottom right, measurement data in blue) with the same incident field strength (14 kV/cm in this case).

References


Local Variations of Light Absorption and Emission in Monolayer WS₂ Flakes

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Abstract

The investigation of the local excitonic response of two-dimensional transition metal dichalcogenides is crucial both for fundamental research and in view of their implementation in novel optoelectronic devices. In this work, we compare the photoluminescence spatial patterns of monolayer WS₂ flakes grown by chemical vapor deposition with their position-resolved dielectric function probed by imaging spectral ellipsometry. The two datasets show both correlated and uncorrelated spatial patterns. Micro-structural variations within the flakes are deemed responsible for the observed discrepancies.

1. Introduction

Group VI semiconducting monolayer transition metal dichalcogenides (ML-TMDs) are characterized by direct bandgaps spanning the near-infrared and the visible spectral ranges. This feature, together with other singular properties, makes ML-TMDs extremely intriguing light-sensitive materials for optoelectronics and photonics applications [1]. Interestingly, the exploitation of characterization methods having a spatial resolution at the micro- and nanoscale has proven pivotal to investigate the physico-chemical properties typical of high quality TMDs grown via chemical vapor deposition (CVD) [2].

The optical response of ML-TMDs is dominated by excitons, i.e. electron-hole pairs interacting via screened Coulomb force. Micro- and nanoscale mapping of excitonic properties of CVD-grown TMDs flakes have been extensively reported by probing their radiative-annihilation characteristics by means of imaging photoluminescence spectroscopy (IPL), while local mapping of the complex dielectric function of ML-TMDs, which describes the light-absorption counterpart, is comparatively much rarer. In this work, we exploit the high sensitivity and sub-micrometric lateral resolution typical of imaging spatial ellipsometry (ISE) to locally map the dielectric function of CVD-grown WS₂ flakes (ε_MS₁) having typical size tens of microns across (Fig. 1a). Correlating ISE and IPL data recorded on the same flake, we unveiled both analogies and differences in the corresponding spatial patterns, ascribed to the presence of well-defined patterns of structural defects, which affect differently the physical processes of light absorption and emission.

2. Discussion

The optical properties of ML-WS₂ flakes grown by CVD and transferred on a silica substrate were investigated by ISE and IPL. Compared to laterally-averaged techniques [3], both ISE and IPL provide additional information by resolving respectively the light absorption and emission properties of materials at the microscale. Concerning ISE, a dedicated and state-of-the-art instrumentation detected the light after its interaction with the sample, by acquiring two angles (Δ, Ψ), defined according to the equation

\[
\tan \Psi e^{i\Delta} = \frac{|r_{p,s}| e^{i(\delta_{p,s})}}{|r_{s}}}
\]

where |r_p,s| and δ_p,s are respectively the amplitudes and phases of the p,s-polarized complex Fresnel reflection coefficients of the sample. The WS₂ flakes were characterized by eleven (Δ,Ψ) maps acquired at selected energies in the range 1.94-2.85 eV. In Fig. 1b,c, we show the ISE data acquired at 2.0 eV, which is very closed to the maximum of the so-called A excitonic peak of ML-WS₂ for the system under investigation.

The emission properties of ML-WS₂ flakes are represented by the intensity, energy and full-width half maximum (FWHM) obtained by fitting the PL peaks of IPL maps (Fig. 1d-f). At first sight, both the ISE and IPL maps show similar patterns, with many local variations across the flake.
A deep investigation on the similarities and discrepancies of the two datasets requires the determination of the local $\epsilon_{WS_2}$. We selected some regions of interest (ROI) on the ISE maps (Fig. 2a) and calculated the average ($\Delta \Psi$) in those regions. By using linear regression analysis without a dispersion model, we assessed the local $\epsilon_{WS_2}$ at each available energy of ISE maps (Fig. 2b).

Our findings confirm that the emission and absorption properties of ML-WS$_2$ are often, but not always correlated. Some examples of correlation are the damping or suppression of the A excitonic features along the bisectors and at the center of the flake, together with the correspondence between the spectral shift of both the A excitonic absorption peak and the PL peak. However, the spatial extension of the detected local variations in the ISE maps is generally smaller than the ones shown in the IPL maps and some local features which are present in IPL intensity maps are absent in ISE maps, and vice versa. Notably, such discrepancies occur on a larger lateral scale than the spatial resolution of ISE and IPL ($\sim$0.5 μm and $\sim$1.5 μm, respectively). Accordingly, we ascribed these differences to the presence of defects in the WS$_2$ structure, which can introduce non-radiative decay channels [4]. Indeed, since the two techniques probe two distinct energetic transitions, they may present a different sensitivity towards the presence of defects, which, finally, explains the differences between the light absorption and emission properties of CVD-grown ML-WS$_2$.

3. Conclusions

We investigated the local excitonic properties of CVD-grown ML-WS$_2$ flakes by means of ISE and IPL. By locally mapping the $\epsilon_{WS_2}$ and the PL peak of ML-WS$_2$, we demonstrated that a correlation between its absorption and emission properties is present, with some exceptions. The presence of structural defects across the flakes can explain the observed differences. More in general, the possibility of mapping the local exciton related properties is fundamental in view of combining 2D semiconductors into heterostacks.

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References

Single-walled carbon nanotube phase shifters for low THz frequencies
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Abstract
In this work single-walled carbon nanotube length dependence on phase tuning properties of dielectric rod waveguide is experimentally studied in ultra-wide frequency band of 0.1-0.5 THz.

1. Introduction
Millimeter-wave and terahertz electronics are experiencing an increasing academic and industrial interest. High frequency devices and systems are relevant for a wide range of applications from telecommunications to medical imaging and diagnosis. Several devices such as attenuators and phase shifters require dynamically tuneable materials, which are usually very lossy at these high frequencies. Metamaterials and nanomaterials, such as single-walled carbon nanotubes (SWCNTs), are therefore widely studied to address this shortcoming. We have recently demonstrated that the dielectric constant of thin SWCNT layers can be optically tuned in the frequency range of 0.1 THz to 1 THz \cite{1,2}. In this work, we show how the dielectric properties of thin SWCNT layers can be used as reconfigurable impedance surface at the low THz frequency band. The impedance of SWCNTs is tuned by light illumination in ultra-wide band of frequency. The tunable layers are integrated with DRWs as optically controlled phase shifters.

2. Experimental
Thin layers of randomly oriented single-walled carbon nanotubes were synthesized by aerosol chemical vapor deposition (CVD) \cite{5}. Three samples with average nanotube lengths were studied: S1 – 30 ± 10 μm, S2 – 20 ± 5 μm, and S3 – 12.5 ± 2.5 μm, estimated from CVD growth parameters according to \cite{6}. The as-grown CNT layers were transferred from cellulose membranes onto other substrates (sapphire DRW, optical glass, polished silicon) by direct dry transfer.

Dielectric waveguide measurements were based on sapphire DRWs with a 60 mm total length, a 1.0 × 0.5 mm² cross-section, and 6-mm-long tapering sections from both sides. The DRWs were mechanically supported by a low-loss foam structure on a micropositioning stage. The tips of the DRW were manually aligned to metallic waveguides, as illustrated in Figure 2. The tapered transition allows the excitation of the $E_{11}^e$ mode in the DRW by the TE$_{10}$ mode in the metal waveguide \cite{7}, \cite{8}. A Rohde & Schwarz ZVA-24 vector network analyzer (VNA) was used for 2-port S parameter measurements with frequency extenders in the 75 GHz to 500 GHz range (waveguide bands WR-10, WR-5, WR-3, and WR-2.2). The CNT samples were cut in ~5 mm by 0.5 mm wide strips and transferred to the narrow wall of DRWs. The illumination was performed with a white LED (wavelength range 430 nm to 630 nm), focused on the CNT layer with a light intensity of 120 mW/cm².

3. Results and Discussion
Due to the open nature of the dielectric waveguide and the evanescent electromagnetic field, materials deposited on the sidewall of the DRW interact with the wave propagation inside the waveguide. The measured S parameters are shown in Figure 3 for all the frequency bands for a reference empty waveguide and DRWs loaded with the CNT samples. The $S_{21}$ and $S_{12}$ were found similar and are omitted for clarity as they do not provide additional information due to the measurement setup's symmetric configuration.

Below 100 GHz, $S_{21}$ decreases with the frequency for samples S1 and S2, and almost no effect is observed for S3. The losses are attributed to the electromagnetic absorption by the CNT layers with differences stemming from variations in nanotube densities and total lengths of the transferred samples on the DRWs. The increased absorbance at lower frequencies has also been previously observed for CNTs \cite{1}.
Figure 2: a) Schematic diagram of the transition between the DRW and metallic rectangular waveguides of different frequency bands. b) Image of the measurement setup.

Figure 3: Measured S parameters of an empty DRW and CNT-loaded DRW. With the increasing frequency, the S$_{21}$ of the reference empty waveguide decreases considerably.

Figure 4: Measured S$_{21}$ phase shift and change of amplitude due to the illumination of the CNT samples on a DRW.

4. Conclusions

Under illumination of the CNT layers, the shift in amplitude and phase of S$_{21}$ were recorded and are illustrated in Figure 4, with the shaded areas corresponding to 95% confidence intervals. The measured S$_{21}$ amplitude shift due to the illumination (normalized by the sample length) indicates almost no effect of light. Not sure about the oscillations at high frequencies. All three CNT samples integrated with DRWs show similar results concerning the generated phase shift under illumination. Illumination of an empty DRW without CNTs does not produce any phase shift as sapphire is transparent in the illumination wavelength range.

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References


Optical antennas and plasmonics-based devices
Self-powered photoresponse enhanced by asymmetrically integrated optical patch antennas in a metal-graphene-metal structure

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Abstract

Optical patch antennas are integrated into the metal-graphene-metal structure in an asymmetrical manner for a prominent self-driven photoresponse. A 105 times high contrast between the photoresponses at the two contact-graphene junctions is achieved; and the responsivity enhancement by this structure is one order of magnitude higher than that by a subwavelength metal grating. The resonant behavior of the antenna enables spectrum-selective photoresponse. The photoresponse time is shorter than several microseconds, and the photoresponse mechanism is mainly attributable to photothermoelectric effect.

1. Introduction

With the emergence of low dimensional optoelectronic materials, such as 2D materials and nanowires, light coupling management becomes extremely important [1-5]. Concerning the simplest device architecture (i.e. active material without built-in potential connected by two contacts), self-driven photoresponse comes from the Schottky-like junction between the active material and the metal contact. The simple architecture allows this type of devices to be compatibly integrated with other systems, and the zero-bias operation ensures low dark current. Although the advantages are obvious, this type of devices suffer from two bottleneck problems: 1) absence of a net self-driven photoresponse under uniform flood illumination, 2) limited photoresponse due to low light absorption in the junction area. In this work, we propose to use asymmetrically integrated optical patch antennas to address the two bottleneck problems simultaneously. The metal-graphene-metal (MGM) photodetectors are the best platforms for this investigation. Due to the locally enhanced absorption of graphene and the enlarged junction area at one contact, and the restrained absorption of graphene at the other contact, a 105 times high contrast between the photoresponses at the two contacts is achieved so that a considerable self-driven photoresponse under flood illumination is obtained. Owing to the efficient light coupling of the optical patch antennas, the responsivity enhancement is one order of magnitude higher than that by a metal grating as a common light coupling structure. Besides, the photoresponse spectrum, time and mechanism are all characterized.

2. Results and Discussion

A typical optical patch antenna consists of a metallic reflector, a dielectric spacer and a top metal patch. This structure is consistent with a MGM transistor once a graphene layer is inserted above the dielectric spacer and below the top metal patch. The bottom metal plane works as the reflector for the optical patch antenna and also as the gate for the transistor. The dielectric spacer is required for both cases. The top metal patch could become an extension of the contacts. As shown in Figure 1a, the patch array elongated in the x direction is integrated with the drain contact only, resulting an asymmetrical integration of the optical patch antennas with the graphene device.

Figure 1: a) Sketch of the optical patch antenna integrated MGM device. b) Photovoltage waveforms obtained by shining the laser spot at the A and the B positions (marked in (a)) for polarization perpendicular to the x-axis. For a better comparison, the signal at the A position is already enlarged by 10 times. c) Sketch of the MGM structure with asymmetrical integrated patch
antennas (top) and the MGM structure with asymmetrically integrated subwavelength metal grating (down) under flood illumination. d) Measured self-driven photoresponse spectra of the two devices. e) SEM images of four optical patch antenna integrated graphene devices with different metal patch widths: 215, 237, 256 and 283 nm. The period is kept the same: ~590 nm. f) Photoresponse spectra of the four devices in (e).

When the optical patch antenna is on resonance [6,7], an intensified local field is generated and strongly interacts with graphene at the drain contact, whereas at the source contact the absorption of graphene is significantly suppressed by the bottom metal plane. As characterized by the photovoltage scanning technique, the photoresponse at the antenna integrated contact is 105 times higher than that at the other contact without top patches. The high contrast is confirmed by the waveforms presented in Figure 1b.

Based on the high contrast between the photoresponses at the two contacts, we could expect net self-driven photoresponse under flood illumination. As shown in Figure 1c, the MGM structure with asymmetrically integrated patch antennas was illuminated by a large laser spot. A considerable self-driven photoresponse with a resonant behavior was obtained, as shown in Figure 1d. For comparison, the asymmetrically integrated subwavelength metal grating with the MGM structure on a SiO2 (300 nm)/Si substrate also shows the net self-driven photoresponse under the flood illumination, but the responsivity is much lower than that in the patch antenna-integrated device. At the resonant wavelength of the patch antenna, the difference in responsivity between the two devices is more than 11 times. For a common MGM device with a symmetrical configuration, there was no signal by this measurement.

The photoresponse spectrum of the patch antenna integrated graphene could be tuned by adjusting the width of the metal patch that decides the plasmonic cavity length. Figure 1e and 1f present four patch antenna integrated graphene structures with different patch widths and the corresponding photoresponse spectra, respectively. With the patch width increasing from 215 nm to 283 nm, the photoresponse peak is red-shifted from 1.30 μm to 1.65 μm. The bandwidths of the photoresponse peaks are around 200-300 nm. The relationship would help us to predict the photoresponse spectrum based on the patch width.

3. Results and Discussion

The optical patch antennas were successfully integrated with MGM photodetectors in an asymmetrical manner to enhance the self-driven photoresponse. This approach addresses at the same time the two bottleneck problems, i.e. photoresponse cancellation due to contact symmetry and limited light absorption of graphene. The effect of the asymmetrical integration of optical patch antennas was demonstrated in the near infrared range in this work, whereas the approach for self-driven photoresponse enhancement could also be applied in other wavelength ranges such as mid-infrared or far infrared, where a higher sensitivity is more desired.

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References

Independent engineering of individual plasmon modes in plasmonic dimers with conductive and capacitive coupling

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Abstract

We revisit plasmon modes in nanoparticle dimers with conductive or insulating junction. In our study which combines electron energy loss spectroscopy, optical spectroscopy, and numerical simulations, we show coexistence of strongly and weakly hybridized modes. While the properties of the former ones strongly depend on the nature of the junction, the properties of the latter ones are nearly unaffected. This opens up a prospect for independent engineering of individual plasmon modes in a single plasmonic antenna.

1. Introduction

Localized surface plasmons (LSP) are self-sustained collective oscillations of free electrons in metal nano- and microstructures (plasmonic antennas) coupled to the local electromagnetic field. LSP resonances can be characterized by electron energy loss spectroscopy (EELS) that utilizes an electron beam that interacts with the metallic nanoparticle and excites the LSP resonances. EELS measures the energy transferred from electrons to the LSP and is sensitive to the electric near field of LSP projected onto the trajectory of the beam.

Properties of LSP can be engineered by adjusting the shape, size, and composition of the plasmonic antennas. Several interesting phenomena and applications of plasmonic antennas involve more than one LSP mode, including directional scattering or Fano resonances [1]. It is thus desirable to engineer individual plasmon modes in a single antenna independently.

Here we present such a possibility. We show that by switching between the capacitive and conductive coupling in bowtie antennas, the properties of some LSP modes are changed pronouncedly while other modes are almost unaffected. We also show that by employing Babinet’s principle [2, 3] it is possible to visualize both electric and magnetic near fields related to a LSP mode.

2. Independent engineering of LSP modes

We have studied four types of plasmonic antennas. Bowtie and diabolo antennas consist of two triangular prisms with an insulating gap or a conductive bridge, respectively. Their Babinet-complementary counterparts (inverted bowtie and diabolo) are apertures in the metallic layer of the same size and shape. The gold antennas have been fabricated by focused ion beam lithography [4] (with the thickness of 30 nm, the junction dimensions 30 × 30 nm², the total length 300 nm).

LSP modes in the antennas have been characterized by electron energy loss spectroscopy (EELS), optical spectroscopy, and electromagnetic simulations. In the following we will discuss only the lowest-order modes: a charge transfer dipolar (CTD), a transverse dipolar (TD) mode, and a longitudinal dipolar (LD) mode. We note that there is a pair of nearly degenerate bonding and antibonding TD mode and in case of the bowtie antenna also LD mode. For the full modal analysis we refer to Ref. [1].

Figure 1: High-angle annular dark field images of the bowtie and diabolo antennas and spatial maps of the loss function at the energy corresponding to specific LSP modes: CTD, TD, LD. The numbers in the left top corner indicate the energy of the mode.

Figure 1 shows the spatial maps of the loss functions and indicates the energies of the three lowest-order modes in the bowtie and the diabolo antenna. Strikingly, the TD and LD modes have nearly the same spatial maps and energy in both antennas, while the CTD mode is present only in the diabolo antenna.

Clearly, the modes can be classified as two different types. Strongly coupled modes (CTD) include either charge transfer through the conducting bridge or capacitive charge coupling at the insulating gap. Their properties strongly depend on the properties of the junction. Weakly coupled modes (TD, LD) exhibit no charge transfer or capacitive...
coupling at the junction, and are only slightly affected by the conductivity of the junction.

The existence of strongly and weakly coupled modes opens a prospect for the independent engineering of individual modes. The procedure is based on changing the conductivity of the antenna at the node of current oscillations of a specific mode. When a conductive connection between the two parts of the antenna is changed to a capacitive connection, the modes with the current node are only weakly modified, while the charge transfer modes are influenced significantly. On the contrary, independent antennas can be conductively connected to form new charge transfer modes.

3. Imaging of the electric and magnetic field

EELS is sensitive to the electric field induced in the plasmonic antennas (the out-of-plane component \( E_z \) parallel with the trajectory of electrons) and can be used for its qualitative visualisation (the quantitative relation is not straightforward [1]). However, EELS is insensitive to the magnetic field. The visualisation of the magnetic field is still possible based on Babinet’s principle, which predicts (with some simplification) the same spatial distribution of the magnetic field \( B_z \) in the antenna and the electric field \( E_z \) in its Babinet-complementary counterpart (the inverted antenna). EELS allows to visualize the electric field in the inverted antenna which is then used to represent the magnetic field in the original antenna.

Figure 2: (top) Schematic representation of the TD LSP mode in the diabolo antenna with calculated electric and magnetic near field distribution. (middle, bottom) Dark field micrographs of the diabolo (middle) and inverted diabolo (bottom) antennas together with measured EELS intensity maps corresponding to TD mode.

We will demonstrate the feasibility of this approach for the TD mode in the diabolo antenna. Figure 2 shows in the top line the scheme of charge oscillations for the TD mode in the diabolo antenna together with the calculated out-of-plane electric and magnetic field. The strongest out-of-plane electric field occurs just near the areas of accumulated charge, i.e., at the corners of the diabolo. Figure 2 (middle) indeed shows maxima of experimental loss intensity at those areas. Similarly, charge node at the horizontal axis of the diabolo is manifested by the minimum of both experimental loss intensity and calculated \( E_z \). Magnetic field in the diabolo antenna according to the Ampère’s law circulates around the electric current, forming two vertical nodal planes for the out-of-plane component. The distribution of magnetic field \( B_z \) in the diabolo antenna is visualized by the experimental loss intensity retrieved for the inverted diabolo antenna, Fig. 2 (bottom).

4. Conclusions

We have demonstrated a unique approach of independent engineering of individual LSP modes in composite plasmonic antennas based on varying the coupling between the components from capacitive to conductive. Taking bowtie and diabolo antennas as an example, we have shown that the longitudinal dipolar mode can be significantly modified without affecting the higher-order modes. This represents a powerful tool for tailoring the properties of LSP modes for the phenomena and applications including Fano resonances, directional scattering, or enhanced luminescence.

Acknowledgement

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References


Plasmonic metasurfaces for magnetic field enhancement at THz frequencies

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Abstract

Enhanced magnetic fields at terahertz frequencies are indispensable in many situations where analysis or modification of magnetic properties of matter is needed. Here we study a plasmonic metasurface formed by diabolo antennas, which exhibits such magnetic field enhancement, and using numerical simulations and subsequent terahertz time-domain spectroscopy we confirm a clear relationship between the antenna geometry and the spectral shape and position of the plasmonic resonance.

1. Introduction

A metal nanoantenna provides maximal enhancement of electric and magnetic fields at resonance. The spatial distribution of these enhanced fields highly depends on the antenna shape. When dealing with the characterization of magnetic materials, enhancement of the magnetic field is often beneficiary. Hence, various antenna geometries have been considered with respect to their magnetic field enhancement, such as split ring resonators, swiss crosses and diabolo antennas [1, 2, 3]. The diabolo shape (Fig. 1a) is generally favoured as the increased current density in the antenna waist leads to enhanced induction of the magnetic field around the waist of the antenna, so called magnetic hotspot. Figs. 1c,d show the field distribution around the diabolo antenna – electric hotspots are located mainly along the edges of the antenna wings, whereas the magnetic field is enhanced mostly around the antenna waist. To find out the dependence of spectral resonance peak position on the antenna geometry and antenna pitch \( p \) (center-to-center distance of neighbouring antennas), we conducted numerical simulations and confirmed the simulated outcomes by terahertz time domain spectroscopy (THz TDS).

2. Discussion

2.1. Numerical simulations

To study the impact of the size of individual features of the antenna on the resonance wavelength and magnetic field enhancement, finite-difference time-domain simulations (FDTD) were conducted using Lumerical FDTD Solutions software. Fig. 2 shows the outcomes of one of such simulations: panel (a) introduces the geometry of the simulated antenna (on a quartz substrate), while panels (b-d) describe the spectral dependence of the antenna scattering cross-section and compare the resonance wavelength and the value of maximal magnetic field enhancement for the varying antenna length. The outcomes of the simulations indicate linear relation between the length and the resonance wavelength of the diabolo antenna. The maximal magnetic field enhancement exhibits a similar trend.

2.2. Sample preparation

Two sets of samples were made by optical lithography, one on silicon \(( n_{Si} = 3.4)\) and the other on quartz \(( n_{Q} = 1.9)\) substrates. Photoresist AZ 1505 was spincoated on the substrates and hard-baked at 100°C for 60 s to produce a 500 nm thin layer. The photoresist was patterned with direct laser writer Heidelberg µPG 101 (375 nm, focal length 10 mm). Subsequent development of the samples in AZ 726 MIF (30 s) created a mask for deposition of 3 nm adhesion layer of titanium and 140 nm of gold by e-beam and ther-
mal evaporation, respectively. Final structures – diabolo antenna arrays with area of $(2 \times 2)$ mm$^2$ – were recovered after lift-off.

2.3. Terahertz time-domain spectroscopy

THz TDS measurements were carried out in reflection configuration, using dasNano Onyx system for thin layer conductivity characterization. The frequencies measured by this THz TDS system are limited to 300–1400 GHz due to signal-to-noise ratio. A single measurement provides a THz TDS map, with each pixel corresponding to a time-domain interferogram. Fourier transform, applied on the interferograms, then leads to an absolute spectrum of the sample reflectivity. To allow for comparison between arrays on different substrates, individual spectra were normalized to the spectra yielded from antenna-free substrates. Figs. 2f,g show the influence of the antenna pitch $p$ (see Fig. 2e) on the shape and spectral position of the plasmonic resonance peak. Within these experiments, different antenna dimensions were utilized, described in the insets of corresponding figures. Higher signals are observed for arrays on quartz substrates, due to its low refraction index. Based on the experimental outcome, a setting of antenna pitch $p = 2L$ was used for further work. Fig. 2h shows the experimental determination of relationship between the length and the resonance wavelength of antenna, located in an array as described afore. The experimental results match the linear trend observed in simulations.

3. Conclusions

We conducted a set of FDTD simulations, which determine the dependence of resonance wavelength of a diabolo antenna on the size of its individual features. Series of various metasurfaces of $(2 \times 2)$mm$^2$ area were fabricated, differing by the used substrate, antenna size and antenna pitch. Prepared samples were characterized by THz TDS. Both simulations and experiments confirm the linear relation between the resonance wavelength of a diabolo antenna and its dimensions. This enables tailoring of the size of a diabolo antenna to desired operational frequency. An optimal setting has been found for antennas on quartz substrates with a pitch of doubled antenna length.

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References


Subwavelength mapping of optical modes in all-dielectric nanoantennas

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Abstract

We report on near-field mapping of higher order optical modes in all-dielectric nanoantennas (rod, disk, square, triangle shape) by using aperture type scanning near-field optical microscopy (SNOM). Nanoantennas have been made of amorphous Si on the glass substrate. The correspondence of the electromagnetic field components of the excited optical modes with features on SNOM maps is demonstrated by means of full 3D FDTD modeling of the scanning process.

1. Introduction

All-dielectric optical nanoantennas are low-loss elements of the modern nanophotonic devices which allow efficient light trapping at the nanoscale owing to the excitation of optical modes [1]. A single, as well as 2D arrays of the nanoantennas allow enhancing nonlinear light generation, fluorescence emission of a single molecules [2], and can alter the light directivity [3]. Engineering and designing the shape of nanoantennas and their dimensions govern the spatial distribution of the available optical modes. Mapping optical modes makes senses in the precise positioning of single quantum emitters and fluorescence molecules on nanoantennas. The subwavelength visualization of Mie and radial optical modes in Si disk, and disk dimers was recently shown by using scanning optical microscopy (SNOM) [4, 5], and cathodoluminescence imagine spectroscopy [6]. However, the near-field distribution of the higher order optical modes in nanoantennas with more complex shapes has not been visualized yet.

2. Results and Discussions

Single nanoantennas with rod, disk, square, and triangle shapes and different dimensions were fabricated from amorphous Si (a-Si) on a glass substrate by e-beam lithography (See SEM images in Fig.1(a)). To visualize the optical modes with subwavelength resolution, we used aperture type scanning near-field optical microscopy in the illumination mode. The SNOM probe is a hollow pyramid covered by a 100 nm Al thin film with a tiny hole of 90 nm diameter at the apex. The incident broadband polarized light focused on the apex of the pyramid (Fig.1 (b) and (c)) creates a strong, localized near-field around the probe. The contact mode of the SNOM probe allows this localized source to excite the optical modes in nanoantennas. The bottom objective collects the scattered light in the far-field and delivers it to a detector.

Typical 3D representation of SNOM maps of an a-Si nanorod with dimensions of $L \times W \times H = 900 \times 170 \times 105$ nm$^3$ is presented in Fig.1 (d) and (e). For TM-polarization of the incident light and $\lambda = 670$ nm, the SNOM map possesses five bright peaks, arising due to the excitation of transverse magnetic (TM) Fabry-Perot mode. However, the SNOM map has six bright peaks when $\lambda = 750$ nm and the polarization is TE, i.e. it is perpendicular to the rod’s axis. To reveal the origin of the bright spots on the SNOM maps, we simulated (FDTD, Lumerical Solutions) the scanning process of the SNOM probe along the central axis of the nanorod. Figure 2 (a) and (c) show that positions of high intensity are in a good agreement with those on experimental SNOM cross-sections. For TM-polarization, the $|H_x|$ field map (Fig. 2 (b)) taken at one of the intensity peaks shows that its z-position corresponds to one of the $H_z$-antinodes. For the TE-polarization (Fig. 2 (d)), the position of $E_y$-antinode corresponds to one of the intensity peaks. Thus, bright spots on SNOM maps coincide with $H_x$-antinodes of the TM Fabry-Perot modes and $E_y$-antinodes for TE modes. SNOM maps are able to visualize the order and parity of Fabry-Perot modes in $a$-$Si$ nanorods, that are forbidden for the plane wave excitation due to the symmetry. SNOM maps of nanoantennas with the shape of the disk, square, and triangle demonstrate excitation and visualization of various higher order optical modes. Their excitation can lead to both bright or dark features on maps depending on their radiative nature.

3. Conclusions

Here, we experimentally applied scanning near-field optical microscopy (SNOM) in the illumination mode to map the higher order optical modes in all-dielectric nanoantennas
Figure 1: (a) SEM images of the fabricated nanoantennas (top view). (b,c) The scheme of the excitation of the TM_{51} and TE_{61} Fabry-Perot modes in a-Si nanorod with the dimension of L×W×H=900×170×105 nm³. (d,e) The 3D representation of SNOM maps of TM_{51} and TE_{61} Fabry-Perot modes in the rod-shape nanoantenna.

Figure 2: (a,c) SNOM maps of TM_{51} and TE_{61} Fabry-Perot modes of a-Si nanorod with L=900 nm. Bottom graphs show the experimental (red curves) and simulated (blue dashed curves) cross-sections of the SNOM maps along the axis of the nanorods. (b,d) The simulate |H_x| and |E_y| components of the Fabry-Perot modes excited by the SNOM probe taken through the central yz plane, respectively.

with complex shapes such as a rod [7], disk, square, triangle. By full 3D FDTD simulations, we demonstrate field distribution of optical modes excited by the SNOM probe and the correspondence of bright and dark spots on SNOM maps with electromagnetic field components of excited optical modes.

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References

Enhanced light generation due to hybridization of lattice and gap plasmon modes in periodic MIM tunnel junction

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Abstract
A promising approach to realize electrically excited on-chip nanoscale optical sources is through inelastic electron tunneling. Its practical implementation, however, suffers from low electron-to-photon transduction efficiencies. Here, we investigate the enhancement of light generation in a periodic Ag-SiO$_2$-Ag tunnel junction due to inelastic electron tunneling. By efficiently coupling lattice resonance with gap plasmon mode, we achieve an enhancement in the local density of optical states by three orders of magnitude and a radiative efficiency 30% higher than the uncoupled structure.

1. Introduction
The study of electrical excitation of surface plasmon (SP) through the process of inelastic electron tunneling (IET) has expanded rapidly in recent years [1-4]. IET based metal-insulator-metal (MIM) tunnel junctions have a potential to create ultra-compact photon and SP sources that can be readily integrated with existing CMOS technologies. The emission through IET can be described as a two-step process: electrons tunneling inelastically through a MIM tunnel junction lose a part of their energy in the barrier to the gap plasmon modes of energy $\hbar \omega$, provided the applied bias $|eV| \geq \hbar \omega$; the gap plasmon mode then decays to emit either photons or propagating SPs.

Though the IET based devices are known for ultra-small device footprint and ultra-large modulation bandwidth, they are plagued by low external quantum efficiencies (EQE). This can be attributed to: (a) a higher elastic electron tunneling rate than the inelastic tunneling rate and, (b) the low radiative out-coupling of the excited gap plasmons to free-space photons. The former can be enhanced by designing a structure with high local density of optical states (LDOS) for gap plasmons within the barrier, and the latter can be overcome by using a plasmonic antenna with high radiative efficiencies. Here, we theoretically and numerically investigate the resonant enhancement in total LDOS and the radiative efficiency of gap plasmons in a 2D periodic Ag-SiO$_2$-Ag structure with a barrier thickness of 3 nm. For a particular periodicity, the highest radiative efficiency is achieved by tuning the width and height of the top electrode. By varying the periodicity, the out-coupling efficiency of the gap plasmon is further improved by ~30%, resulting from the strong coupling between the gap plasmon mode and the lattice resonance.

2. Results and Discussion
The simulated structure depicted in Fig. 1. On the application of bias voltage, photons are emitted from the junction as a result of quantum-mechanical tunneling (see inset of Fig. 1). The efficiency of IET as a source of gap plasmon can be described using Fermi’s golden rule, and it depends on the applied bias and the total LDOS. The total light emission then depends on the efficiency with which the antenna radiates out the gap plasmon mode, i.e. the radiative efficiency of the antenna. The spectrum of emitted radiation is modelled by the relation [2]

$$\rho_{\text{emission}} \propto \left( 1 - \frac{\hbar \omega}{eV_b} \right) \frac{\rho_{\text{total}}}{\rho_0} \times \eta_{\text{rad}},$$

(1)

where $V_b$ is the applied bias voltage, $\rho_0$ is the vacuum density of states, $\rho_{\text{total}}$ is the total LDOS, and $\eta_{\text{rad}}$ is the radiative efficiency of the antenna, calculated as the ratio of the radiative to total LDOS. Higher values of $\rho_{\text{total}}$ improve the overall tunneling efficiency, and a higher $\eta_{\text{rad}}$ increases the overall radiative efficiency of the emission spectrum.

![Figure 1: Structure consists of a continuous silver film of 200 nm thickness with a 3 nm thick SiO$_2$ deposited on top. The top electrode consists of a periodic silver nano-strip antenna ($\Lambda = 400$ nm) of $w = 35$ nm and $h = 80$ nm. The inset depicts the generation of photons through inelastic electron tunneling when $V_{\text{bias}}$ is applied across the tunnel junction.](image)
To model the optical response of the device, we use the commercial Finite Difference Time Domain (FDTD) solver Lumerical FDTD™. The normalized total and radiative LDOS for a 400 nm periodicity structure [Fig. 2(a)] shows a good ~3 orders of magnitude improvement over vacuum, with the fundamental gap plasmon mode occurring at a wavelength of 698 nm. The H-field distribution in Fig. 2(b) indicates that the fundamental mode is highly concentrated within the gap and is magnetic dipolar in nature with dipole moment in the z-direction. The peaks at lower wavelengths correspond to higher-order magnetic dipolar modes due to the Fabry Pérot cavity formed as seen in Fig. 2(c). The radiative efficiency of the fundamental mode for the structure is found to be ~0.41.

To study the effects of varying periodicity on the radiative efficiency of the tunnel junction, reflectivity versus wavelength is calculated with varying periodicity and plotted in Fig. 2(d). A dip at the longer wavelength corresponds to the gap plasmon mode and at the shorter wavelength corresponds to the surface lattice resonance (SLR). Increasing periodicity results in an anti-crossing between the two modes at a periodicity and wavelength of ~700 nm and 698 nm respectively, indicating a region of strong coupling between the SLR and gap plasmon mode. The total and radiative LDOS at the optimum periodicity of 700 nm for wavelengths of interest are shown in Fig. 2(d). The two peaks at the gap plasmon resonance at 698 nm and 724 nm wavelength are in excellent agreement with the corresponding reflectivity dips for a periodicity of 700 nm, indicating the hybridization of the gap plasmon and lattice resonance modes. The corresponding H-field profiles for the two peaks [Fig. 2(f, g)] show a significant emission in top half-space, indicating the efficient out-coupling of gap plasmon to free-space radiation. The radiative efficiency for 700 nm periodicity is found to be ~0.53, an increase of ~30% compared to the uncoupled structure.

3. Conclusion

In conclusion, we numerically investigated the light generation through inelastic electron tunneling in a periodic Ag-SiO₂-Ag tunnel junction. IET efficiently excites the gap plasmon mode with high local density of optical states within the barrier. We explored the interplay between gap plasmon and lattice resonance by varying the periodicity of the structure. An anti-crossing between the two modes was observed due to the hybridization of the lattice resonance and gap plasmon mode, leading to an enhancement in the radiative efficiency by ~30% as compared to the uncoupled structure.

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References

Plasmonic color filters: angular dependence

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Abstract

Plasmonic color filters promise a potential solution to miniaturization of color-filtering elements in modern devices. Yet, the dependence of plasmonic filters’ spectral responses on the incident angle of light rays has been addressed minimally. In this work, we analyze the angular dependence in plasmonic color filters consisting of nanoholes in metallic film. For these purposes, various plasmonic color filtering arrays (differing in structure size, shape, periodicity, etc.) were characterized with transmission optical spectroscopy for nonzero incident light angles.

1. Introduction

In everyday objects and devices, color filtering is often realized with various dyes and pigments. The undeniable advantage of these mechanisms, dwelling in the relative stability and large variety of achievable colors, gets nowadays slowly outbalanced by the lack of lateral resolution provable by such filters. An attractive solution to this problem has been introduced in form of plasmonic color filters [1]. Composed of either nanoholes in metallic films or standalone metallic nanostructures, these filters rely on easily tunable plasmonic resonances which occur at metal-dielectric interfaces. By altering the geometry of these filters (nanostructure’s size, shape, periodicity, and their lateral arrangement) or the materials used in them (metallic parts and materials of the adjacent dielectrics), various resonance conditions can be achieved, i.e., various colors can be filtered in both reflective and transmissive regimes.

In this study, we focus on one of the less-tackled challenges in plasmonic color filtering: namely, what is the change in the spectral response of a color filter if illuminated under a nonzero incident angle. In many works related to this subject, any discussion regarding the angular dependence of the color-filtering performance was avoided with little to no analysis of its origins. The observed angular dependence has been put in connection with the lattice resonances tied to the nanostructure arrays and thus solved by randomization of the nanostructure locations and/or use of cross-shaped apertures in metallic films, which balance the angle-originating resonance mismatch via their geometry [2,3]. In the presented study, the angular dependence of plasmonic color filters is analyzed in detail, so that other approaches to this challenge may be revealed.

2. Discussion

2.1. Numerical simulations

To design plasmonic nanostructures suitable for color filtering at optical frequencies, finite-difference time-domain (FDTD) simulations were conducted using Numerical FDTD Software. Based on these simulations, we chose to further examine holes in thin aluminum film on fused silica substrate. Various color filtering pixels were designed, differing in the geometry of their nano-features (square, cross, line, ...) and the size and shape of the 2D lattice filled with said nanofeatures. Balancing between high transmission intensity and narrow transmission maxima observed in simulation outcomes, square-like nanoholes arranged into a hexagonal lattice seemed the most suitable for further investigation. Later, these FDTD simulations were compared with experimental results from transmission optical spectroscopy.

2.2. Sample preparation

Fused silica substrate was covered by 100 nm thin aluminum layer using e-beam evaporation. Three polymer layers were spin-coated on the sample surface (AR 300-80, AR-P 6200.09 and AR-PC 5090 from Allresist) to be further structured via e-beam patterning with a Tescan Orsay® MIRA3 system. To ensure the correct structure size, e-beam doses of 100-160 µC/cm² were used at 30 keV during patterning with ca. 30 pA beam current. After sample development (AR 600-546 for 60 s, IPA for 30 s), the structured resist acted as a masking layer for reactive ion etching. To anistropically etch through the metallic layer unprotected by the resist, a mixture of BCl₃ and Cl₂ was used (6:1 to etch away the ever-present oxide layer, then 1:3 for aluminum etching). Finally, the remaining resist mask was dissolved in dioxyolane.

3.3 Far-field optical spectroscopy

In investigation of the optical transmission spectra of the plasmonic color filters, the sample was positioned on a tiltable x-y stage and was illuminated by a 100 W halogen lamp (400-950 nm range) through a Nikon 10x objective (NA=0.30). The light source was spatially limited to ensure...
that only paraxial light rays interact with the sample. The light was collected using the second 10x objective of the same type, which directed the light into the input slit of an Andor® Shamrock 303i spectrometer system equipped with an iDus camera.

To allow for comparison of the color-filtering performance of the fabricated plasmonic filters, their relative transmittance is presented, denoting the transmittance normalized with respect to the spectra obtained when light propagated through the experimental setup with no sample present. Fig. 1 shows the angular dependence of three plasmonic color filtering arrays (array area (20x20) μm²) designed to transmit blue, green, and red colors, respectively. Insets in the plots show micrographs of these nanohole filters and denote the hole size w and the periodicity of holes p. With increasing angle of incidence, losses in transmission intensity and redshift of the transmission maxima are observed, pronounced especially in filters optimized for longer wavelengths. Interestingly, the nonzero incidence transmission peaks remain ‘inside’ the corresponding zero-angle transmission maxima. Hence, no new additional wavelengths are introduced to the filters’ transmission spectra with alternations in the incident angle of light rays.

Figure 1: Angular dependence of the blue, green, and red color filter transmission. Dotted lines represent simple averages of the plotted spectra. The inset micrographs (scale bar: 300 nm) show SEM images of the corresponding nanohole arrays and denote the hole size (w) and periodicity (p).

Our further experiments on plasmonic color filtering include the comparison of angular dependence in filters composed of holes with other shapes (annular rings, triangles, …), filling the holes of the fabricated filters with dielectric (thus increasing the effective refractive index of these structures) and defining the spectral crosstalk of neighboring nanohole arrays for creation of high resolution color images.

3. Conclusions

Based on FDTD simulations, various nanohole arrays in aluminum film were designed to achieve color filtering plasmonic arrays. Using electron beam lithography and selective reactive ion etching, the proposed filters (standard area (20x20) μm²) were fabricated. The functionality of these filters was probed with far-field optical spectroscopy in transmissive regime. Great attention was paid to the performance of these filters under various angles of incident light and means for minimizing the dependence of filtered colors on the angle of incident light rays.

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References

Numerical study of the optical properties of disordered metallic grooves by a one-mode analytical model

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Abstract

Metallic grooves of sub-wavelength dimensions behave like Fabry-Perot nano-cavities able to resonantly enhance the electromagnetic field. In this summary, the consequences of positional disorder on the optical behavior of groove arrays are presented. We show, with a specifically developed simulation tool, that disorder leads to a redistribution of energy compared to the periodic case. By studying arrays of variously shaped grooved, we also show that their optical response can be described by the individual sub-array responses.

1. Introduction

Fabry-Perot nanocavities are commonly used resonators for metasurface design, because their optical behavior is very useful for various applications in photonics and optics [1, 2]. These cavities can be vertical (MIM) or horizontal (grooves), while having the same properties. Here, metallic grooves were chosen to study how the optical response of a resonator array is modified by the introduction of positional disorder.

The simulation tool used for this study is based on a one-mode hypothesis to describe the field within the metallic grooves [3]. This hypothesis allows for faster computations of the optical response of large surfaces, as required to model non-periodic structures. With this numerical model, it is shown that the proportion of the incoming energy scattered by a disordered resonator array is equal to what is diffracted by the corresponding periodic array. This energy redistribution is also resonant, and wavelength-selective when more than one type of resonator is on the surface [4].

2. Groove disorder

The resonators studied here are metallic grooves of given depth and width and of infinite length, as shown on Figure 1a). These grooves are first studied when they are placed in a periodic array, and then their positions are gradually disordered by increasing the disorder factor (DF). This DF is the width of the zone in which the position of each groove is picked at random within a uniform distribution. Therefore, for a periodic array, DF = 0, and the array is more disordered for larger DF.

On Figure 1b) is shown the reflection spectrum of the studied periodic groove array. It exhibits two resonances, the fundamental groove mode at 14.2 \(\mu m\) and a corresponding higher order at 4.65 \(\mu m\). Higher orders of the Fabry-Perot mode are also present at shorter wavelengths, not shown on the figure. The resonance at \(\lambda_r = 4.65 \mu m\) is chosen for future computations, in order to have diffracted orders, because it is smaller than the array period of \(L_x = 6 \mu m\).

![Figure 1](image-url)

Figure 1: (a) Groove array studied, with groove dimensions \(h = 3 \mu m\), \(w = 0.25 \mu m\), and \(L = 6 \mu m\). (b) Reflection spectrum of this metallic groove array. (c) Specular reflection (R), diffracted orders (D), scattering (S) and absorption (A) depending on the Disorder Factor, at \(\lambda_r = 4.65 \mu m\).
On Figure 1c) is represented the evolution, when DF is increased, of specular reflection, diffracted orders, scattering and absorption at $\lambda_r$. This shows that the absorbed and reflected fractions of the incoming energy remain nearly constant when DF increases. This reinforces the interpretation of scattering as being the disordered equivalent of diffracted orders, and also shows that the maximum scattered energy (large DF) is equal to the energy diffracted by the periodic array (DF = 0).

3. Bigroove disorder

Bigroove arrays, i.e. arrays of metallic grooves composed of two alternating groove geometries, are now studied. These structures have spectra with independent resonances and allow the study of the diffraction to scattering conversion selectivity. For this, two independent disorder factors (DF1 and DF2) are defined, to control the positional disorder of each groove type. The position of each groove is now picked at random within a uniform distribution of width given by the DF corresponding to their groove type.

On Figure 2 are shown the spectra of a fully disordered structure (a) and of a mixed structure (b). It can be observed that the disorder-induced scattering is resonant, i.e. only present at the resonances of the disordered grooves. Therefore, in the mixed structure the optical response of the ordered grooves is not modified by the disorder of the other grooves.

This resonant and selective behavior allows the conception of surfaces with varied and controlled spectral responses, as on Figure 2 b) where some wavelengths are fully absorbed, some are scattered and some other are diffracted by the structure.

4. Conclusions

We have studied the optical behavior of disordered groove and bigroove arrays. To this end, we developed a single simulation tool based on an analytical one-mode model. We have shown the resonant behavior of these structures and the effects of disorder on their spectral response. The study of structures with different groove geometries also confirmed that the effects of disorder are selective, allowing the design of surfaces with complex and well controlled spectral behaviors.

Acknowledgement

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References


Figure 2: Reflection (R), diffracted orders (D) and scattering (S) spectra computed for disordered (a) and mixed (b) bigroove arrays of period 6 $\mu$m and dimensions ($w^{(1)} = 0.25 \mu$m, $h^{(1)} = 3 \mu$m) and ($w^{(2)} = 0.25 \mu$m, $h^{(2)} = 2 \mu$m).
Plasmon-enhanced photovoltaics, photocatalysis, and solar fuels
Light trapping with subwavelength compound parabolic concentrators

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Abstract

Light trapping and the broadband absorption of the solar radiation is of interest to solar energy applications. In the current work, we report a new paradigm for light trapping, that is light trapping based on arrays of subwavelength nonimaging light concentrators (NLCs). We numerically show that NLC arrays provide ~50% broadband absorption enhancement of the solar radiation compared with that of optimized nanopillar arrays. We show that CPC arrays (in contrast to nanopillar arrays) function as anti-transmission layers.

1. Introduction

Light trapping is about capturing photons from an incident electromagnetic wave, and it is particularly important to solar energy conversion1-4. The Yablonovitch limit (the ergodic limit) is a thermodynamic limit based on statistical ray optics that predicts the maximum light trapping possible in a homogeneous semiconducting film5,6, and defines the minimum absorber thickness needed to fully absorb the solar radiation. Furthermore, arrays of semiconducting subwavelength structures introduce additional localized trapped modes (Mie modes) to the optical system. The presence of Mie modes and hybridization of these with the other modes allow for light trapping beyond the Yablonovitch limit7. Callahan et al showed that the Yablonovitch limit can be exceeded by allowing high density of local optical states in the absorber8. Yu et al developed a statistical temporal coupled-mode theory that demonstrated beyond the Yablonovitch limit using wave optics9.

In the current study we further explore light trapping with arrays of NLCs. Recently we numerically demonstrated broadband absorption with arrays of light funnels (LFs)10-15. We showed that with LF arrays the absorption enhancement of the solar radiation is more efficient than the absorption of optimized NP arrays and is superior to other advancements in the field. Interestingly, a LF is nothing else but a LC NLC16.

2. Materials and Methods

We use a 3D finite-difference time-domain (FDTD) electromagnetic simulations using Advanced TCAD by Synopsis (Mountain View, CA, USA). The simulations are for silicon nonimaging light concentrators, and the CPC equations are taken from reference10. The calculations are performed in the spectrum range of 400-1100 nm in 20 nm steps. For efficient and accurate FDTD simulations, the maximum mesh cell size is kept smaller than 1/10th of the wavelength in silicon (more than 10 nodes per wavelength). The considered solar spectra is Air Mass 1.5 Global (AM 1.5G). The optical constants of silicon material are taken from the literature17.

3. Result and Discussion

Figure 1a shows an illustration of a CPC array. Figure 1b present relative absorption spectra of a thin film, an optimized NP array (period and diameter of 500 nm and 400 nm, respectively17), an LC NLC array, an ellipsoid NLC array, a hyperboloid NLC and a CPC array (heights of 1 µm). Evidently, the broadband absorption of the selected NLC arrays is significantly higher than that of a thin film and of an optimized NP array, and exhibit strong spectral absorption peaks. The Yablonovitch limit is also shown for reference, and noticeably, while the NP array spectrum lies well below the limit, the spectra of the NLC arrays approach, for certain wavelengths, the Yablonovitch limit. Also, note that in Figure 1b (1 µm height) the spectra get closer to the limit. Figure 1c presents the respective ƞabs. The transition from thin film to NP array concludes an ƞabs enhancement of ~40% for height 1 µm. The deformation of the NP array into LC NLC arrays generates an additional ƞabs increase of 50% and 24% for the 0.5 µm and 1 µm array heights, respectively. And the transition of the LC array into either ellipsoid NLC array, hyperboloid NLC array or a CPC array results in a further ƞabs enhancement (additional 13% increase for the 1 µm CPC array). This is particularly interesting as an LC is a primitive NLC with poor concentration ratio, while the other NLCs have superior concentration ratios (e.g. 3D CPC being almost ideal and hyperboloid NLC is an ideal concentrator). This alludes a certain correlation between the concentration ratio of the individual NLCs and the broadband absorption of the respective array. Finally, further optimization of the NLC geometries provides even higher ƞabs enhancement as shown for the CPC array with top diameter (Dt) of 300 nm (array height 0.5 µm). Figure 1b-c suggest that the underlying light trapping mechanism in NLC arrays is substantially more efficient than that of NP arrays.

Finally, we examine the PV performance of a single unit cell in a CPC array. The geometry of the considered CPC array is 600 nm period, top diameter of 500 nm, bottom diameter of 100 nm and height of 750 nm. We compare the PV performance of the CPC unit cell with the PV performance of single unit cell in an optimized NP array with a period of 500 nm, NP diameter of 400 nm and 750 nm height. The main electrical concern is the increase in surface recombination due to a surface-to-volume ratio
(S/V) of the 3D subwavelength features. Therefore, we select an axial junction configuration as it is more susceptible to surface effects than a radial structure.\(^{18,19,20}\) Figure 1d inset presents the 3D electron density distribution in short-circuit conditions for both structures. Also, the location of the metallurgical junction (yellow line) and the boundaries of the depletion regions are marked (white lines). Note the smaller depletion on the emitter side (n-type, phosphorus doping of $5 \times 10^{19}$ cm\(^{-3}\)) and the greater depletion on the absorber side (p-type, boron doping of $10^{18}$ cm\(^{-3}\)).

A 1D curves show the electron densities along the z-axis in the middle of the structures. The higher electron density in the CPC is a direct consequence of the higher absorption. Also, note that both systems are in the low injection regime with a $10^{10}$-10\(^{11}\) electrons/cm\(^2\) in the absorber. Figure 1d shows the current vs. voltage (I–V) curves for a base doping level of $10^{18}$ cm\(^{-3}\) for both structures. The short-circuit current density (Jsc) of the CPC PV cell is >75% higher than the Jsc of the NP PV cell.

**Figure 1.** a. An illustration of a cubic CPC array under normal illumination. The color code reflects the excitation of various Mie modes. b. Absolute absorption spectra for various NLC arrays for heights of 1 \(\mu\)m. The period is 0.5 \(\mu\)m and Dr =400 nm. The relative absorption of the respective thin film and optimized NP array are shown as well. c. The weighted absorption corresponding to the spectra in Figure 1b. d. L-V curves for base doping level of $10^{18}$ cm\(^{-3}\). Inset: distribution of electron densities.

### 4. Conclusions

The current work numerically demonstrates efficient light trapping with arrays of subwavelength CPCs. We show that CPC arrays are characterized by small transmission and high reflection, in contrast with NP arrays that are known for their anti-reflection properties. We suggest that light trapping in CPC arrays is mainly due to efficient occupation of Mie modes, which is consistent with the inherent light concentration capabilities of individual CPCs. We believe this work motivates future research in the field of light trapping with NLC arrays.

**Conflicts of Interest:** The authors declare no conflict of interest.

### References

High-Index Optical Metamaterial for Perovskite Solar Cells

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Abstract
Recently, perovskite solar cells have attracted considerable attentions from the solar cell society due to their exotic properties such as high quantum efficiency and low recombination rate. However, the power conversion efficiency (PCE) of the perovskite solar cells, reported thus far (~25%), is not yet comparable to their fundamental limit (referred to as Shockley-Queisser Limit). Here, we show that an increase in refractive index of perovskite via high-index optical metamaterial can further enhance the PCE of solar cell.

1. Introduction
In recent years, the field of perovskite solar cells have seen a rapid surging of interest owing to their exotic properties (a full solution-based versatile and cost-effective access to superior optoelectronic properties) [1]. PCE of ~ 25.2% is among the highest [2]; but, it is still below the fundamental thermodynamic limit of perovskite solar cell, defined by Shockley-Queisser Limit [3-6]. Here, we introduce the use of high-index optical metamaterials can lead us to further increase the PCE of perovskite solar cells. In particular, we take the concept of high-index optical metamaterial to boost light trapping effect [7] within active layer and show how short-circuit current ($J_{sc}$) can benefit from the enhanced light trapping [8]. Finally, we explore how an increase in the refractive index of perovskite active layer affects the thermodynamic limits of solar cell.

2. Result and Discussion
Toward this, we use detailed balance analysis to exploit the fundamental thermodynamic limit of the high-index optical metamaterial perovskite solar cell [8]. The high-index optical metamaterials with perovskite medium are designed, which could be realized with the currently accessible self-assembly method [9,10]; their effective refractive index ($n_{eff}$) is systematically obtained by s-parameter retrieval method [11].

2.1. Design of high-index optical metamaterial in perovskite
The $n_{eff}$ of medium can be unnaturally increased by the implementation of the regularly arrayed metal nanoparticles (NPs) [8-10]. Especially, the electric dipoles (EDs) can be strongly induced within each NP (acting as electric meta-atom); then, the capacitive coupling between the induced EDs can dramatically enhance the polarization ($P$) and resultant effective permittivity. Overall, the including of metallic NPs and coupling them with a few nanometer-gaps can increase $n_{eff}$ unnaturally [8-10].

Given such design rule, we arrange rectangular shape aluminum NPs (Al NPs) in perovskite medium to effectively increase $n_{eff}$ (Fig. 1 (a)). We use Al NPs rather than Ag/Au NPs because their absorption, resulting from both the interband transition and resonance behavior (i.e., Kramers-Kronig relation), can occur below 400 nm wavelength, which is not spectrally overlapped with the absorption and luminescence spectra of perovskite [8].

![Figure 1: (a) Schematic for the high-index optical metamaterial perovskite solar cell. (b) Calculated effective refractive indices of perovskite active layer with high-index optical metamaterial. Concentrations of Al NPs are controlled by gap of Al NPs.](image)

As expected, $n_{eff}$ of perovskite can be indeed increased far beyond the naturally accessible regime by implementation of Al NPs (Fig. 1 (b)). In particular, a smaller gap between Al NPs can give rise to a higher $n_{eff}$ because the underpinning mechanism for these high-index optical metamaterials depends on the capacitive coupling between the induced ED in each meta-atom, as mentioned earlier.

2.2. Detailed balance analysis
Once the available $n_{eff}$ of perovskite is defined by effective medium theory, we systematically exploit the fundamental thermodynamic limit of the high-index optical metamaterial perovskite solar cell by using detailed balance analysis [3-6,8]. We briefly introduce this calculation method in this section.
2.2.1. General equations

We use a ray-optically approximated Yablonovitch limit (4r_{att}^2 limit) [7] to calculate the fundamental absorption limit of the high-index optical metamaterial perovskite solar cell [4-6,8]:

$$a(E) = \frac{4n_{eff}^2 \alpha d}{4n_{eff}^2 \alpha d + \sin^2 \theta_a}$$  \hspace{1cm} (1)

where \(\alpha\), \(d\), and \(\theta_a\) are absorption coefficient, solar cell thickness, and maximum angle of emission, respectively. The \(J_{sc}\) and open-circuit voltage \(V_{oc}\) are defined as follows [4-6,8]:

$$J_{sc} = \frac{q}{\Phi_s} \int_{0}^{\infty} a(E) \Phi_s(E)dE$$  \hspace{1cm} (2)

$$qV_{oc} = qV_{oc,\text{max}} - kT \ln \eta_{ext}$$  \hspace{1cm} (3)

where \(a\), \(\Phi_s\) and \(\eta_{ext}\) are absorptivity, solar radiation, and external luminescence of cell, respectively.

2.2.2. Detailed balance analysis

Total current density \((J_{total})\) is influenced by following components such as generated short circuit current, radiative recombination current loss \((J_{rad})\), Auger recombination current loss \((J_{Auger})\), and Shockley-Read-Hall recombination current loss \((J_{SRH})\) [4-6,8]:

$$J_{total}(V) = J_{sc} - J_{rad}(V) - J_{Auger}(V) - J_{SRH}(V)$$  \hspace{1cm} (4)

2.3. Calculation results

![Figure 2: Calculated performance of high-index optical metamaterial perovskite solar cell under ideal condition (no loss mechanism and with perfect mirror). (a) \(a\), (b) \(\eta_{ext}\), (c) \(J_{sc}\), (d) \(V_{oc}\) and (e) PCE.](image)

We find that an increase in \(n_{att}\) of perovskite leads to the enhancement of absorption \((a)\) (Fig. 2(a)) and reduction of \(\eta_{ext}\) (Fig. 2(b)). \(J_{sc}\) can be increased (Fig. 2(c)), resulting from the enhanced absorption according to the light trapping (proportional to \(4n_{att}^2\) [7]). In contrast, increasing \(n_{att}\) should narrow the escape cone and thereby reduce the \(\eta_{ext}\). Consequently, \(V_{oc}\) falls down (Fig. 2(d)) according to the Eq. 3. Conclusively, \(J_{sc}\) and \(V_{oc}\) trade off each other, when light trapping is boosted via increasing \(n_{att}\). Fortunately, the benefit from the boosted \(J_{sc}\) can compensate the defeated \(V_{oc}\). As a result, the enhancement of PCE can be attained via an increase in \(n_{att}\) and resultant light trapping (Fig. 2(e)).

3. Conclusions

We implemented the concept of the high-index optical metamaterial to boost the \(4n_{att}^2\)-based light trapping effect in the perovskite solar cell. Even if \(V_{oc}\) should fall down, the enhanced light trapping of the perovskite active layer by using the high-index optical metamaterial can still lead us to improve the PCE of solar cells. Our metamaterial approach can provide a viable and readily translatable meta-optic platform for the innovation of solar cells.

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References

Ultraviolet radiation impact on the efficiency of crystalline silicon-based photovoltaics

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Abstract
We evaluate the ultraviolet radiation impact on the temperature and efficiency of realistic photovoltaic modules. We perform this investigation for crystalline silicon-based photovoltaics that operate outdoors, by employing a thermal-electrical modeling approach, which takes into account all the major intrinsic processes affected by the temperature variation in the photovoltaic devices.

1. Introduction
A commercial PV’s degradation is mainly attributed to the degradation of the eminent polymer encapsulant ethylene-vinyl-acetate (EVA) copolymer, employed as adhesion layer/layers between the cells [see Fig. 1(a)]. The photochemical processes caused by light, such as photodegradation, lead to the alteration of the primary structure of the polymer, due to the breaking of the chemical bonds in its main chain, initiating unwanted reactions [1]. Such photochemical processes are a major material-degradation factor resulting even to reduced transmission from the EVA (yellowing) and thus harming PV’s performance significantly [2]. Ultraviolet (UV) radiation has been identified as the most critical factor for this degradation and for the degradation of photovoltaics in general [1,2]. High energy UV photons (0.28–0.4 μm) can break chemical bonds in the main chain of the EVA-polymer as well as cause damage to the front surface of the silicon layer (i.e., defects, acting as recombination traps). Moreover, high energy UV photons (~0.28-0.4 μm) result in significant heat dissipation (often called thermalization losses [3]) that increases the PV temperature and thus decreases its efficiency; this is due to the excess of the UV photon energy relative to the semiconductor’s bandgap energy. In this respect, it is crucial to evaluate UV impact on the efficiency of a PV and examine whether it is advantageous to block it and up to which extent. For this evaluation, we consider realistic commercial crystalline silicon PVs [4] and we employ a thermal-electrical co-model (described in Ref. [4]), which calculates the solar cell steady-state temperature (for a given incident power, materials, and environmental conditions), as well as its efficiency as a function of temperature, taking into account all the major intrinsic processes affected by the temperature variation in a commercial PV device. These processes include the material-dependent radiative and non-radiative-Auger recombination of electron-hole pairs, which is a major cause for the voltage decline and the subsequent efficiency decrease of PVs operating at elevated temperatures [3,4]. Employing our model, in Section 2 we explore the impact of the UV radiation (on the PV temperature and efficiency) by gradually reflecting it (by 100%), starting from a wavelength equal to 0.28 μm - where the highest thermalization losses occur, up to a given, critical wavelength λr, and we evaluate the critical wavelength λr as to achieve maximum temperature reduction and maximum efficiency. Finally, we demonstrate our findings with a realistic structure, i.e., an one-dimensional photonic crystal acting as an optimized UV reflector [5].

2. Results
Figures 1(b) and 1(c) show the PV temperature change [Fig. 1(b)] and the PV efficiency change [Fig. 1(c)] resulting from total reflection of the solar energy from 0.28 μm to a parameter (critical) wavelength λr as λr varies from 0.28 μm to 0.45 μm. For the calculations, we assumed that the PV operates outdoors, with variant environmental conditions (different combined conduction-convection nonradiative heat transfer coefficient related to the changes of the wind speed, h_c, different ambient temperature, T_amb, and different irradiance levels, Irrl). As seen, in Fig. 1(b), reflecting incident radiation always leads to a temperature reduction (compared to the primary PV, i.e., without UV reflection), as expected. Interestingly though, reflecting UV radiation up to a specific wavelength (depends on the environmental conditions) leads to an increase (up to ~0.1%) rather than a decrease of the PV efficiency, despite the reduction of potential carriers. In other words, the high EVA absorption [green dashed line in Fig. 1(c)] in this regime and the
thermalization losses seem to overcompensate the positive impact of the additional potential carriers generated by the UV [see the blue area in Fig. 1(c)]. Moreover, performance is not sacrificed even for a λ~0.375 up to 0.393 μm [right vertical red, black lines in Fig. 1(b), (c)] despite reflecting UV radiation, while the PV temperature further reduces.

Fig. 1. (a) Schematic of the silicon-based PV module. (b) PV temperature and (c) efficiency change associated with the reflection of the incident UV, for a reflection wavelength range from 0.28 μm to λ. For all cases, T_{amb} is equal to 298 K. We assume an irradiance level (Irrl) of 40% (of the “AM 1.5G” standard sunlight spectrum [6]) and a combined nonradiative heat transfer coefficient, h_c, equal to 20 W/m²/K (black lines), Irrl=100%, h_c=20 W/m²/K (blue lines), and Irrl=100%, h_c=10.6 W/m²/K (red lines). The green dashed line in (c) indicates the EVA absorption. The two black/red dashed vertical lines correspond to two different λ_c of 0.363/0.37 μm and 0.375/0.393 μm, where we observe the maximum efficiency improvement and the limiting point, where the efficiency remains unharmed for the conditions of the black/red curve case. The orange and blue filled areas correspond to the normalized “AM 1.5G” standard sunlight spectral irradiance and photon flux, respectively.

To demonstrate our findings with a realistic system we utilize the PV device of Fig. 1(a) covered by an one-dimensional (1D) photonic crystal (PC), acting as UV reflector — see Fig. 2(a). The proposed 1D PC consists of 45 alternating Si3N4 (relative permittivity ε~4) – MgF2 (ε~1.82) thin layers and effectively reflects part of the UV spectrum. As can be seen in Fig. 2(b), the 1D PC not only reflects the high-energy UV photons (i.e., at wavelengths, ~0.28-0.44 μm) but also increases PV’s top surface transparency compared to the flat glass at the higher wavelengths, i.e., ~0.44-1.1 μm, leading to increased photocurrent. This increased photocurrent led to an efficiency increase [up to ~0.25%, Fig. 2(c)] higher than the one achievable by assuming only UV reflection [~0.1%, Fig. 1(c)]. From the efficiency increase of Fig. 2(c), as shown by our calculations, ~0.11% is the contribution of the increased photocurrent while the increase from ~0.11% up to ~0.25% comes from the maximum power point voltage, V_{mp}, increase [Fig. 2(c)], resulting from the UV reflection and the consequent temperature reduction. Summarizing, the implementation of the 1D PC at the PV device of Fig. 1(a), and assuming T_{amb}=298 K and Irrl=100%, led to a PV efficiency increase always higher than 0.19% and a temperature reduction higher than 1 K.

Fig. 2. (a) Illustration of a 1D photonic crystal (consisting of alternate Si3N4 – MgF2 thin layers of 15 – 100 nm thickness respectively – total thickness ~2.6 μm) placed on top of the PV. (b) Reflectivity spectra of the 1D photonic crystal (blue line) in comparison with the reflectivity of flat glass [i.e., the top layer in Fig. 1(a) – green line]. The two black dashed vertical lines correspond to two different λ_c of 0.363/0.375 μm discussed in connection with Fig. 1. (c) PV temperature reduction (black line), efficiency increase, and maximum power point voltage, V_{mp}, increase (green line) with the utilization of the 1D PC of (a), for T_{amb}=298 K Irrl=100%, with respect to the h_c.

3. Conclusions
In conclusion, we examined the role of the ultraviolet spectrum on the efficiency of commercial crystalline silicon-based PVs operating outdoors. We observed that by implementing a photonic approach to effectively reflect UV radiation we can increase both the efficiency and the lifetime of the solar cells providing thus an effective alternative, to the existing costly techniques, for screening UV.

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References
Local intensity enhancement and Purcell factor in hyperbolic metamaterials – spontaneous emission engineering

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Abstract

In this work, we theoretically study the quantum mechanisms that are an effective tool for analyzing the increase in the photonic density of states (PDOS) in relation to hyperbolic metamaterials (HMMs). Numerical results of the Purcell factor of HMM stack built on the basis of alternating layers of silica and silver are reported. We theoretically show that interplay of plasmon polaritons leads to an increase in the spontaneous emission and, as a result, to an increased PDOS. In particular, such properties enable us to use them to quantum computers, plasmonic resonators and multi-functional nanophotonic systems. Importantly, such functions of HMMs are crucial from the point of view of state-of-the-art nanophotonic technologies.

1. Introduction

Hyperbolic metamaterials (HMMs) represent a new class of plasmonic materials, that exhibit hyperbolic dispersion when they interact effectively with incident radiation. Their exotic electromagnetic properties i.e.: negative refractive index, near-zero or indefinite permittivity or permeability, backward waves propagation, usually depend on the material properties of the insulating and conducting layers on the basis of which the stack is built. Thanks to this, they create a unique tool for manipulating electromagnetic waves. Furthermore, these unique properties are crucial for many advanced photonic applications of HMMs, e.g.: in ultra-high resolution microscopy, imaging systems, sensing and cloaking, as well as thermal and spontaneous emission engineering [1,2]. Interestingly, nanostructured metamaterials with hyperbolic dispersion can cause tremendous increase in PDOS [3]. Consequently, a large PDOS of HMMs is an enhanced decay rate of quantum emitters in HMM stack. Importantly, this enhancement can be expressed by the Purcell factor which strongly depends on PDOS [4].

There are two types of HMMs: Type I HMMs ($\varepsilon_{xx} = \varepsilon_{yy} > 0$, $\varepsilon_{zz} < 0$) and Type II HMMs ($\varepsilon_{xx} = \varepsilon_{yy} < 0$, $\varepsilon_{zz} > 0$). While the PDOS for an ideal and homogeneous HMM diverges, the increase in the spontaneous emission of dipole emitters is observed. This leads to a broadband Purcell effect and this gives the possibility to control gain/absorption in tunable hyperbolic metamaterials. PDOS is a subject to formalism and the principles of quantum mechanics, which means the discretization of possible energy values with a certain number of available states [1,3]. The PDOS, like its counterpart for electrons, is very important in the design of advanced electronic and photonic devices that use resonant quantum phenomena. An emitter located within the HMM structure has more decay channels in accordance with the Fermi’s golden rule, which enhances its spontaneous emission. Therefore, placing a dipole near the HMM structure will result in spontaneous emission or its enhancement, which is stimulated by resonant energy transfer (RET) between the generated localized surface plasmon resonance (LSPR). This RET follows the quantum energy transfer mechanism proposed by Förster. The phenomena described above can be explained in a simplified way by analyzing the modified Jabłoński Diagram in the Fig. 1 below [5,6].

![Modified Jabłoński Diagram](image)

Figure 1. Modified Jabłoński Diagram – as a result of excitation, absorption occurs from the ground state $S_0$ to the excited state $S_e$. LSPR occurs as a result of RET between the excited state $S_e$ of the exciton, while stimulating the emission.

Purcell factor $F_P$ describes the enhancement or inhibition of the spontaneous emission rate of an emitter in a cavity compared to emission in free space. Purcell factor for a randomly oriented dipole on the surface of HMM structure can be more conveniently described as the mean of a dipole oriented parallel and perpendicular to the main optical axis of the HMM structure, according to equation (1) below: [7]

$$F_{PISO} = \frac{1}{3} F_P \perp + \frac{2}{3} F_P \parallel$$ (1)
2. Discussion

2.1. Choice of materials

Hyperbolic dispersion can only be obtained by selecting materials whose dielectric permittivity values are equal but opposite in sign for a given frequency. In particular, this condition is verified for many metal-dielectric pairs, nevertheless when losses are included in the analysis, to satisfy this condition becomes challenging. For instance, due to its high losses, gold has to be excluded and, in order to move the desired condition within the visible range, a high or middle index dielectric needs to be chosen, thus excluding the most commons Al₂O₃ and TiO₂. In the present work, silver has been used as metal because of its low loss at visible frequencies, whereas SiO₂ constitutes an attractive alternative to a common dielectric, due to its wide utilization in current optoelectronic technology, fabrication processes and transparency in most of the visible range and a sufficiently high refractive index. Considering the above, we focused our attention on a SiO₂/Ag pair. Considered HMM stack consists of alternating metallic and dielectric layers (d₀ = dₘ = 20 nm). In our approach we consider HMMs stacks with N = 5, 10, 15 and 20 unit cells.

2.2. Numerical results

The full-wave numerical simulations were carried out using high-performance nanophotonic simulation software ANSYS/Lumerical employing the transfer matrix method [8-11]. In our approach permittivity of Ag layers was described by the Drude model. Data necessary for modeling thin layers of Ag and SiO₂ were taken from database of the software. Simulation results of permittivity components of HMM structure Ag/SiO₂ are illustrated in Fig. 2.

![Figure 2](image2) Real (Re) and imaginary (Im) parts of the permittivity tensor components ε₀ and ε₁. These results show that our HMM structure exhibit Type I hyperbolic dispersion in the range of 0.32 – 0.37 μm and above 0.37 μm turns into Type II hyperbolic dispersion. Simulation results of Purcell factor of the dipole placed on the top of the HMM structure are illustrated in Fig. 3.

![Figure 3](image3) Purcell Factor for dipole placed on the top of the Ag/SiO₂ HMM stack for N = 5 unit cells. The highest value of $F_{P,ISO} = 84$ was observed at a wavelength of 0.37 μm. For the dipole oriented perpendicularly to the HMM stack maximum value of $F_{P,⊥} = 244$ at a wavelength of 0.38 nm, and for the dipole oriented parallel maximum value of $F_{P,∥} = 30$ at a wavelength of 0.33 μm.

3. Conclusions

In this work, results of numerical simulations of the Purcell factor for a dipole placed on the top of a multilayer HMM stack are presented. We showed that the value of $F_P$ is strongly related to the orientation of the dipole with respect to the HMM stack. As a consequence, such HMMs can be used for controlling PDOS. Besides, theoretical results suggest that it is much easier to induce amplification of the spontaneous emission of a dipole located on the top of the HMM. Such layered plasmonic systems are ideal candidates for use in advanced and multifunctional nanophotonic platforms.

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References

Nanoscaled VO₂ insulator-to-metal transition controlled by plasmonic single-nanoantenna

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Abstract

Resonant plasmonic nanoantennas are known to concentrate light at the nanoscale around its surface. VO₂ is of interest for its insulator-to-metal transition when heated up above the relatively low critical temperature of 68°C. In this study we show how the plasmonic feature of a single antenna can be used to induce and control the insulator-to-metal transition in a VO₂ film.

1. Introduction

Gold single nanoantennas are well-known for addressing plasmon excitation when illuminated at a specific wavelength [1]. This plasmon excitation gives rise to, e.g., enhanced light extinction, antenna heating and electromagnetic field concentration close to the antenna surface [2]. This last effect allows to manipulate light at the nanoscale by strengthening the light-matter interaction and the non-linear response [3].

Plasmonic antennas are often combined to active materials, namely materials whose property change under the application of an external stimulus, in order to obtain metasurfaces with enhanced optical properties. As an example, magneto-optical materials [4], giant-magneto-resistance materials [5] and phase transition materials [6] have attracted a wide interest in the latest years. Among the phase transition materials, VO₂ is one of most studied because its insulator-to-metal transition, induced by heating, occurs at relatively low critical temperature (68°C).

In this combined experiential-theoretical study we show how single plasmon nanoantennas can be used to induce phase transition in a VO₂ film. The single antenna also permits to actively control the regions where the phase transition occurs down to the nanoscale. This capability of the antenna-VO₂ hybrid is desirable for the realization of nanoscaled nonlinear optical devices and switches.

2. Experimental and Modelling

Gold single nanoantenna with size 312 nm x 105 nm x 50 nm (length x width x height) was fabricated by e-beam lithography on top of a 50 nm high VO₂ film, which was deposited on a 30 nm high FTO film and a SiO₂ substrate.

The spatial modulation microscopy (SMM) technique was used for single-antenna spectroscopy, namely to obtain the normalized spatial modulation transmission of the single antenna ($T/T_{SMM}$), where $T$ is connected to the difference between the transmission of the system with and without the antenna. A pump-probe scheme was employed to investigate the effect of pumping the antenna at a wavelength of 1060 nm and with an energy of 0.6 nJ. Numerical simulations by means of the Finite-Element-Method were performed in order to reproduce the optical response and understand the underlying physical mechanism. The theoretical normalized differential transmission of the system with and without the antenna ($\Delta T/T_{SMM}$) was calculated through hybrid optical-thermal multiphysics simulations. For accurate results, a bi-dependent temperature-wavelength modelling of the complex permittivity of the VO₂ was developed.

3. Discussion

Figure 1A shows the longitudinal spatial modulation transmission of the system obtained under no pump (black curve) and a 0.6 nJ pump with polarization parallel (blue curve) and perpendicular (red curve) to the antenna length. The peak in the spectra is ascribable to the plasmon excitation in the antenna. For both polarizations the pump produces a red-shift of the peak and a decrease of the optical response, with respect to the no-pumped system. The theoretical results, displayed in Figure 1B, are qualitatively in agreement with the experiments, confirming that our modelling is well-suited. The red-shift of the plasmon peak for the pumped systems is due to creation of VO₂ regions around the antenna where the permittivity decreases, even if a metalization is not reached. This is revealed by the
maps of the simulated pumped-system temperature (Figure 1C and 1D, for parallel and perpendicular pump polarization, respectively), where hot-spots with increased temperature, with respect to the starting sample one of 45°C, appear around the antenna. Even if this higher temperature is not enough to obtain a complete metalization (observed for T > 90°C), the reached value leads to a permittivity close to zero, making the system of interest for applications based on epsilon-near-zero materials. The dependence of the size, shape and position of the hot-spots on the pump polarization explains the difference observed between the blue and red curves of Figure 1A and 1B.

4. Conclusions

Our study demonstrates how plasmonic single antenna can be used to achieve an active control of the VO₂ down to the nanoscale. In this direction, we showed how the geometry of the nanoantenna is a key-parameter in determining the size, shape and position of the phase changed hot-spots in the VO₂ film. The studied antenna-VO₂ hybrid is of paramount interest for the realization of non-linear thermo-optical nanodevices, like thermal memristor and optical switches.

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References

Super-resolution imaging
Exploring object sub-wavelength features using transformation-optics based imaging systems

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Abstract

The information about the fine sub-wavelength details of an object are carried by waves with high transverse wave vectors which become evanescent and decay exponentially inside a classical material. The proposed optical imaging systems made of transformation-optics inspired lenses are capable to process the waves with high transverse wave vectors and enable their contribution to the reconstructed image. The capability of these optical imaging systems to perform magnified images of sub-wavelength features of arbitrary objects is theoretically analyzed.

Inside a classical material the wave vectors of a plane wave satisfies the following equation

\[ k_x^2 + k_y^2 + k_z^2 = n^2 \omega^2/c^2, \]

where \( n \) is the refractive index of the material, \( \omega \) is the frequency of the plane wave and \( c \) is the light velocity in free space. For the waves with transverse wave vectors

\[ k_z = (n^2 \omega^2/c^2 - k_x^2 - k_y^2)^{1/2}, \]

will have an imaginary value. Hence, the waves with high transverse wave vectors which carry information about the fine sub-wavelength details of the object become evanescent and decay exponentially inside a classical material. Consequently these waves will not contribute to the reconstructed image of the object [1].

Recently a transformation-optics inspired design for a flat lens was proposed [2]. The inhomogeneous and anisotropic media comprising the lens is obtained by applying a transformation of the initial space only along one direction (e.g. the \( z \)-axis). In the case when the coordinates are transformed by the following equations

\[
\begin{align*}
x' &= x \\
y' &= y \\
z' &= z/h(x,y),
\end{align*}
\]

where the transformation function is given by

\[ h(x,y) = m \left( \delta - \gamma (\varphi^2 + x^2 + y^2)^{1/2} \right), \]

the resulting transformed media will act as a perfect converging flat lens, for a plane wave propagating parallel to \( z \)-axis. The lens will have a focal distance \( \varphi \), a thickness \( d = 1/\gamma \), \( \delta = 1 + \varphi \gamma \) and \( m \) is a scaling factor. A plane wave propagating inside the proposed lens along \( z \)-axis will always have a real longitudinal wave vector \( k_z \) equal to the transformation function \( h \). Hence, however large the transverse wave vector will be, the waves cannot become evanescent inside the lenses of the proposed optical system. The proposed optical systems are capable to process the high spatial frequencies of the object without converting them in evanescent waves [3, 4].

The proposed optical system consists of two converging flat lenses called the object and image lens and having the focal points denoted by \( F_o \) and \( F_i \), respectively. The lenses have the same thickness, \( d = d_i \), and focal length, \( \varphi_o = \varphi_i \). The media of the object and image lenses are generated by transformation functions \( h \), having the parameter \( m \) equal to 1 and 1/4, respectively. The object lens is embedded in the free space (\( \varepsilon = \mu = 1 \)) while the image lens is embedded in a dilated space (\( \varepsilon = \mu = 1/4 \)). In these conditions, the magnifying power of the system will be equal to four. An absorbing layer, of length \( a \), inserted between lenses, has the role to provide an even distribution of the electric field at the output plane of the device.

The response of the designed optical device is analyzed in a two-dimensional simulation setup which reduces the computations to the field components \( \{E_x, H_y, H_z\} \). The numerical simulations are performed in \((y-z)\)-plane using a two-dimensional finite-difference-time-domain (FDTD) algorithm. When the lenses of the studied device are confined to positive optical parameters, the span of the system on \( y - \) axis is delimited by the singularity points

\[ y_s = \pm \varphi (\rho (\rho + 2))^{1/2}, \]

where \( \rho \) is the thickness to focal distance ratio of the lenses (\( \rho = d / \varphi \)).

Figure 1(a) depicts the real part of the electric field intensity \( E_x \) for three electric dipole sources generated by electric currents parallel to \( x \)-axis. The sources are placed as follow: one in the object focal point \( (F_o) \) of the system and the other two symmetrically with respect to \( z \)-axis at a distance equal to \( \lambda / 2 \) from the focal point \( (F_o) \), where \( \lambda \) is the free space wavelength of the sources. The central source
Figure 1: (a) The real part of the $E_x$ component of the electric field in the simulation area of the $(y-z)$–plane. The thickness $(d_o, d_i)$ and focal length $(\varphi_o, \varphi_i)$ of the object and image lenses as well as the thickness of the absorbing layer $a$ and other dimensions of the simulation area are expressed as multiples of free space wavelength $\lambda$ of the dipole sources. (b) Electric field intensity $(E_x E_x^*)$ inside a square of side length $8\lambda$ having in its center the object focal point (see left green square in fig. 1(a)). (c) Electric field intensity $(E_x E_x^*)$ inside a square of side length $8\lambda$ having in its center the image focal point (see right green square in fig. 1(a)).

and the side sources are out of phase (i.e. dephased by $\pi$). The optical system used in this simulation setup has a magnifying power equal to four. Figure 1(b) shows the intensity inside a square area of side length $8\lambda$ surrounding the object focal point. The dipole sources are clearly observed as the points with the highest intensity. Figure 1(c) shows the intensity inside a square area of side length $8\lambda$ surrounding the image focal point. The images of the dipole sources are clearly observed as three areas of high intensity.

The theoretical study shows that the proposed optical system is capable to reconstruct magnified images of subwavelength features due to its ability to transmit the waves with high transverse wave vectors without transforming them in evanescent waves.

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References

Plano-Convex-Microsphere (PCM) super lens for direct laser nano-fabrication and optical super-resolution imaging in far-field

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Abstract

This paper proposes and demonstrates a high-performance all-dielectric compound superlens, formed by integrating a conventional Plano-Convex lens with a high-index Microsphere lens. We call such new lens the Plano-Convex-Microsphere (PCM) lens, which is developed for far-field super-resolution applications. The compound PCM lens is highly versatile and can be simply adapted into an existing optical system to realize super-resolution function. In this paper, the super-resolution features of the PCM lens were demonstrated for two applications: direct laser nanofabrication and white light nano-imaging. The lens can be naturally extended to other super-resolution applications including sensing, trapping and more.

1. Introduction

One of the great challenges in optical lens design is to break the diffraction limit. Recently, using dielectric microsphere as a nearfield lens for sub-diffraction fabrication and imaging has attracted great interests. The optical phenomenon known as “photonics nanojet” was shown to contribute to light focusing to break the diffraction limit [1]. Researchers have achieved sub-diffraction features fabrication (~λ/3) through laser-induced microsphere lens technique [2]. Subsequent developments in this technology have made it possible to process arbitrary sub-diffraction patterns on sample surface [3]. On the other hand, the prominent characteristic of microsphere lens has also gained a lot of attention in application of super-resolution imaging following our pioneering paper published in 2011 [4]. Unlike other super-resolution imaging techniques, microsphere superlens provides a real-time visualization under white-light illumination, meanwhile, it is label-free and low intrinsic loss at higher optical frequency. Numerous advances in microsphere-based techniques have been made by a number of groups in last decade, for instance, solid-immersion microsphere lenses, microsphere-based confocal microscope for resolving sub-50 nm, nanoparticle-based metamaterial hemisphere superlens, biological superlens using spider silks and cells, and tip-based microsphere scanning techniques [5].

Although literatures revealed the capability of sub-diffraction fabrication and imaging for microsphere-based superlens, there have been few reports that a microsphere lens design can feature both functions concurrently. Recently, manipulation of a single microsphere lens by tip-based scanning techniques were demonstrated for complex nanopattern processing with in situ super-resolution imaging [6]. However, it worked in the near-field modes and required sophisticated and costly near-field tip control system. In this work, we employed a new design where the lens is a compound part consisting of a Plano-Convex lens and a microsphere lens (in short “PCM”), which not only can perform as individual optical probe, but also is able to be perfectly fitted onto an ordinary objective lens to form a unibody PCM-objective lens. This PCM lens design is highly adaptable, meaning that existing optical systems can be converted to super-resolution feature by simply installing the PCM lens. Nano-patternning and nano-imaging experiments were carried out respectively by adapting the PCM lens in a laser marking system and an ordinary microscope system. The results demonstrate that this new design has raised the usability of microsphere-based superlens technique to a new level.

2. Experimental Setup

Fig. 1 shows the schematic of experimental setup. The PCM lens is presented in the form of combination of Plano-convex microsphere lens. A Barium Titanium Glass (BTG) microsphere with diameter of 20-80 μm was aligned and attached onto a curved surface of a BK7 Plano-Convex lens by PDMS or UV glue to form partially encapsulation of BTG microsphere. In the experiments, the fabrication and imaging were implemented by adapting PCM lens onto two optical setups respectively. In the laser fabrication, the PCM lens was simply aligned to a femtosecond laser beam to produce highly enhanced photonic nanojet on to sample surface, as Fig. 1(b) shown. While, imaging function was realized by fitting the PCM lens onto an objective lens (40× 0.6NA) through a custom-designed adjustable adapter. The PCM-objective lens was then installed onto a self-built optical system, as Fig. 1(c) shown. In both experiments, the PCM lens was kept static and the sample was pinpointed by moving the underlying high-resolution nano-stage.
3. Results and Discussions

3.1. Laser direct nano-writing

Figure 2 indicates capability of sub-diffraction laser patterning by PCM lens. The feature size is between 230 nm ($\lambda$/3.5, at 800 nm) and 350 nm ($\lambda$/2.5), depending on laser parameters, when PCM lens scanned in non-contact mode with 2-$\mu$m distance away from sample surface, as shown in Fig. 2(a,b). Meanwhile, arbitrary complex patterns were generated with programmed stage scanning. Moreover, we have extended this method to other materials, such as nickel [Fig. 2(e)] and glass substrate [Fig. 2(f, g)]. The average processing resolution on glass substrate was measured as 354 nm.

3.2. Large area nano-imaging

Large-area nano-imaging was performed with a semiconductor IC chip and Blu-ray disc samples to demonstrate the feasibility of scanning imaging using a developed PCM lens, which is shown in Fig. 3. The IC chip in Fig. 3(a) has features of 200 nm and 400 nm, was imaged by 38 $\mu$m microsphere with working distance around 2.8 $\mu$m. Then the sample was moved in XY plane following the scanning path as yellow dash line showing in Fig. 3(b). The camera captured one frame for every 1 $\mu$m the stage travelled and totally 10×10 images were recorded. The finalized stitched image was demonstrated in Fig. 3(b). Similar scanning experiments were also performed on a Blu-ray disc sample (100 nm grooves and 200 nm stripes) [Fig. 3(c, d)] and more complex structures of the IC chip [Fig. 3(e, f)]. The system has calibrated resolution of $\lambda$/3 in far-field air condition, numerical aperture 1.57, and working distance of 3.5 $\mu$m.

4. Conclusion

In summary, we have developed a compound PCM lens by tactfully integrating microsphere lens onto convex-plane lens. It is advantageous to simplify the optical system and improve usability in practical operation. A typical calibrated resolution of $\sim \lambda$/3 can be achieved in air and far field condition. This lens design is versatile, making it convenient to turn a normal laser marking system or microscope into a super-resolution capable system without affording too much expense.

References

Investigation of proximity effects in light funnel arrays using near-field optical microscopy

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Abstract

Broadband absorption is pivotal for the realization of green energy based on solar energy. Decoration of photovoltaic cells, for example, with arrays of subwavelength formations provides an efficient means for broadband absorption in thin films. Surface arrays of silicon light funnels (LF) were suggested as a promising platform to produce broadband absorption that is considerably superior to that of the well-known nanopillar (NP) arrays, for example. The current study explores the underlying mechanism of broadband absorption in LF arrays. To this end the optical near-field of LF and NP arrays is experimentally probed. We show that in LF arrays the near-field increases as the array period decreases in contrast with NP arrays in which the near-field decreases with decreasing array period. For example, in diluted arrays the near-field intensity of the NP array is ~2.4 times higher than that of the LF array, whereas for compact arrays the near-field intensity of the LF array is ~2.4 times higher than that of the NP array. Also, it is shown that the arrays near-field follows the numerically calculated absorption cross-section of the individual NPs/LFs nested in the arrays. Therefore, it is suggested that the
origin to the broadband absorption in compact LF arrays is due to field overlap of adjacent LFs which increases the absorption cross-section of the individual LFs composing the array. This enhancement in the absorption cross section and the higher filling ratio in compact arrays produce broadband absorption that is significantly higher than that of optically-optimized NP arrays.