Simulating metal and graphene based hybrid plasmonic devices

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Abstract- We present an overview of the main challenges when simulating metal and graphene based plasmonic devices combined with other materials such as organics and semiconductors. We review the different numerical methods and demonstrate how they can be used to efficiently design and optimize plasmonic devices. Examples include gap SPR waveguides coupled to nanoantennas, graphene-based silicon modulators, and plasmonic enhanced solar cells.

Plasmonic structures have the ability to confine light into volumes well below the standard diffraction limit. By combining plasmonic structures with an organic or semiconductor material, one can build a hybrid device with properties that significantly surpass what can be achieved classically. For example, both silicon and organic solar cells with plasmonic structures can lead to increases in optical absorption in the active layers [1, 2], and a hybrid plasmonic approach can be used to build electro-optic modulators with performance characteristics well beyond what is possible with any traditional design [3, 4].

Since the fabrication and characterization of plasmonic devices remains expensive and time consuming, researchers usually have to rely on computer simulations for the design phase. However, the numerical simulation of hybrid plasmonic devices comes with many challenges, beginning with the issue of resolving sub-wavelength geometric structures and the highly localized, discontinuous and even singular electromagnetic fields that can occur in them. In addition, many simulations are necessarily broadband, and the strongly dispersive nature of both the plasmonic materials and the semiconductor or organic materials must be taken into account. Especially for the case of graphene and other two-dimensional materials, the treatment as a bulk material is physically questionable and requires sub-nanometer resolution which can increase simulation times by orders of magnitude over standard photonic simulations. Simulations may involve different illumination conditions, especially solar cells which require different angles of incidence and polarizations. Finally, the full simulation of many complex hybrid plasmonic devices such as solar cells requires electrical as well as optical simulation.

While there are a wide variety of numerical methods available for plasmonic simulations, we can broadly characterize most methods according the spatial grid that is used (finite-difference or finite-element) and whether they are time domain or frequency domain. Time domain simulations with explicit updates are often preferable to frequency domain when broadband results are required or when a large number of grid points are used. This is because the entire spectrum can be obtained from a single simulation and the performance scales well with parallelization. For smaller simulations involving 2D cross sections, for example to calculate the eigenmodes of a waveguide, frequency domain simulations can be preferable. Probably the most commonly used all-purpose simulation method is the finite-difference time-domain (FDTD) technique.

In this presentation, we discuss a series of recent advances with respect to the simulation of hybrid plasmonic devices in the FDTD approach, including some new methods for the simulation of graphene as a 2D material within a 3D mesh [5]. Finally, we present the implementation of a novel split-field technique which enables the broadband simulation of periodic plasmonic devices under oblique illumination in a single
simulation. In contrast to commonly used methods, our implementation is independent of the material properties and works for all linear dispersive media, including metals, graphene, semiconductors and organics.

Some example applications are shown in Figures 1-3. Figure 1 shows a gap SPR waveguide fed by a nanoantenna [6] for coupling with focused beams and compares the power coupling efficiency with endfire coupling as a function of beam NA. Figure 2 shows the propagation of light in a slotted graphene waveguide originally introduced in [7] with and without a bias voltage. Figure 3 shows a plasmonic enhanced Si solar cell, similar to the design in [8] and the resulting field enhancement at 620nm.

Figure 1. A nanoantenna feeding a gap SPR waveguide (inset) and the resulting comparison of power coupling efficiency compared to endfire coupling for different NA beams.

Figure 2. Electric field amplitude along the propagation axis (z) of a slotted graphene waveguide with (a) and without (b) a bias voltage.

Figure 3. Si solar cell enhanced with silver particles (above) and the comparison of the absorption profile at 620nm.

REFERENCES