Opto-Mechanical Interactions in Split Ball Resonators

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Abstract — We demonstrate that a gold split-ball resonator in the form of a spherical nanoparticle with a cut supports optical magnetic and acoustic modes, which are strongly co-localized near the cut, enabling strong opto-mechanical interactions. We simulate the excitation of the acoustic vibrations through laser heating and optical forces induced by the optical magnetic resonance, and determine that a laser pulse which gives 100K temperature change yields acoustic oscillations resulting in 10% modification of the optical scattering.

Designing the magnetic response of light is an essential ingredient to the development of multiple applications based on meta-materials. It was recently shown that metallic spheres with a specially designed nano-cut called Split Ball Resonators (SBRs) can provide a strong magnetic response at visible optical wavelengths combined with ultra-high near field enhancement [1]. On the other hand, it was shown that controlled phonon excitations in nanoparticles can have multiple applications for spectroscopy and sensing [2, 3]. In this work, we predict that strong opto-mechanical interactions can occur in SBRs with a specially designed nano-cut, enabling an efficient way for the controlled phonon excitation by photons.

Figure 1: (a) Schematic of optical excitation of acoustic resonance in SBRs of 100 nm radius and 15 nm wide nano-cut. (b) Normalised electric, polarisation and magnetic field distribution, from left to right, in $y=0$ plane. Maximum amplitude in each figure is normalised to unity (dark red) and minimum to zero (dark blue). (c,d) Temporal profiles of acoustic oscillations excited through (c) laser heating and (d) optical force represented by the displacement in $x$ direction at the nanocut tip points ($x=7.5$ nm, $y=0$ nm, $z=99.7184$ nm) (solid lines) and ($x=7.5$ nm, $y=0$ nm, $z=99.7184$ nm) (dashed line). The time axis is normalised to $T=1/1.33GHz$, the period of the acoustic eigen mode shown in (a). The distributions of the heat power density and the optical force density are shown in the insets of (c) and (d), respectively.

We find that an SBR made of gold supports magnetic optical and acoustic eigen-modes, both of which have highly confined field around the cut, see Figs. 1(a,b). Such localization away from the bottom of the particle is expected to lead to a much higher quality factor of the acoustic oscillation comparing to the nano-antennas involved in previous studies [2, 3] when the particle is positioned on a substrate, since in our case the anchor loss is suppressed. As a result of the strong opto-mechanical coupling ensured by the highly co-localized fields, when a plane-wave pulse excites the optical resonance mode, it can then efficiently drive the acoustic vibration through laser heating or optical forces. We model the mechanical vibration with the following equation,

$$\rho \frac{\partial^2 \mathbf{u}(r, t)}{\partial t^2} = \nabla \cdot \left( C : \frac{(\nabla \mathbf{u}(r, t))^T + \nabla \mathbf{u}(r, t)}{2} \right) + \mathbf{F}(r) \cdot p s(t) \quad (1)$$
where the driven force distribution $F(r)$ can be either due to the the local temperature change or the Lorenz force density, or the sum of both. The local temperature rises from the ambient temperature because the SBR is made of gold which is dispersive and absorbing at optical wavelengths. The mean quantity of heat absorbed into the gold SBR, see Fig. 1(c) inset for distribution, is given by the time-averaged rate of change of the optical energy [4]. The optically induced force is estimated by the time averaged Lorentz force density which is located at the boundary due to the bounded charges and in the volume due to the induced currents in absorbing materials, see Fig. 1(d) inset for force density profile in the $y = 0$ plane.

We simulate the acoustic oscillation in a SBR with radius of 100 nm and nano-cut width of 15 nm under the optical excitation through laser heating and optical forces, considering these effects separately to identify their relative contributions. The time-dependent simulations are performed with the solid mechanics module of COMSOL software using the parameter values of Young’s modulus $E = 70$ GPa, poisson ratio $\nu = 0.44$ and mass density $\rho = 19300$ kg·m$^{-3}$ assuming a moderate mechanical quality factor of 10. Under a plane wave pulsed pump, we observe an excitation of the acoustic eigen mode at frequency 1.33 GHz, shown in Fig. 1(a), which is confined at the top of the lobes at each side of the cut with an anti-symmetric deformation with respect to $x = 0$. We thus characterize the mechanical deformation magnitude of the excited acoustic oscillation by the displacement of the tips of the lobes, the points at $(x = \pm 7.5$ nm, $y = 0$ nm, $z = 99.7184$ nm), and show the time evolution of the acoustic vibration in Figs. 1(c,d) using time axis normalized to the period of 1/1.33GHz. The deformation induced by laser heating, shown in Fig. 1(c), features opposite offsets at opposite sides of the cut representing its thermal expansion nature whereas the Lorentz force drives the lobes oscillating anti-symmetrically around their original positions, see Fig. 1(d). Under a single pulse excitation heating up the SBR by 100 K, the acoustic vibration induced by laser heating changes the nano-cut edge position by 200 pm and the acoustic vibration induced by optical forces shifts the nano-cut edge by 10 pm. We note here the acoustic oscillation amplitude can be further enhanced though excitation by a laser pulse train with the repetition rate matching the eigen-frequency of the acoustic mode. The enhancement factor will be proportional to the mechanical quality factor, which in an SBR is expected to be quite high (up to $\sim 10^9$) due to the absence of the anchor loss on a substrate.

The effect of excited acoustic oscillations on optical waves is then calculated by the simulation of optical scattering cross section of the deformed SBRs. The maximum sensitivity of the scattering response is 0.05% pm$^{-1}$ and it is achieved at the lower half maximum frequency of the optical resonance. This result confirms the efficient opto-mechanical coupling and suggests that 10% modification of total scattering can be detected by a probe laser.

In conclusion, we predict strong opto-mechanical coupling in SBRs. Under an optical pulsed pump which induced 100K temperature change of the nanoparticle, both the laser heating and the optical forces lead to the excitation of the same acoustic mode with different magnitudes of 200 pm and 10 pm, respectively. Such deformations lead to a total scattering modification of 10% for a probe laser. Such strong opto-mechanical coupling in SBRs suggests promising applications such as surface-enhanced Raman spectroscopy and detection of localized strain.

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