Plasmonics and Metamaterials meet Opto-mechanical Applications

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Optical forces are of significant interest from both fundamental and applicative point of view and already proven to be important in various fields of science, from astronomy to biology. Typical optical forces achievable with reasonable light intensities are, in nano-to-pico Newton range, which creates certain limitation on the size of the objects to be manipulated due to their stochastic interactions with their surrounding, e.g. Brownian motion and viscosity of a surrounding liquid, if present. One of the very promising and already tested approaches for optical force enhancement relies on the increase of the field gradient with the help of so-called plasmonic nanostructures. Noble metals with negative permittivity at optical and infra-red wavelengths (plasmonic metals) can support surface plasmon modes with the deep subwavelength localisation of the electromagnetic energy, overcoming the conventional diffraction limit [1] and creating strong field gradients. For example, the concept of plasmonic tweezers has certain advantages providing better spatial localization of objects and reduction of required illumination power due to the antenna effect of trapping structures [2]. The idea of the environmental structuring may be pushed even further, introducing artificially structured media - metamaterial. Generally, metamaterials provide vast of opportunities to manipulate light beams in an uncommon way [3], promising a wide range of potential applications. Metamaterials have also a striking effect on radiation pressure, reversing it direction and attracting negative index bodies, as was shown in [4] with experimental demonstration to follow [5].

In this contribution we will demonstrate several novel effects, related to classical and quantum opto-mecanical effects, inspired by plasmonic nano-structures and metamaterial assembly. In particular, novel quantum-mechanical theory of self-induced torque acting on a dipole situated in structured material environment with arbitrary absorption, dispersion and spatial variations will be presented. The theoretical framework is based on the radiation reaction approach and the rigorous Langevin local quantization of electromagnetic excitations in coordinate domain. We show that this torque does not necessarily dependent on the reflected waves from material boundaries and can emerge in spatially homogeneous structures. Here we investigated radiating dipole, like chemically excited polar molecule, situated in anisotropic, but homogeneous, material [6]. We further demonstrated, that dipole situated within hyperbolically anisotropic metamaterial applies giant self-induced torque and aligns itself in the direction perpendicular to the negative component of the permittivity tensor (Fig. 1). The magnitude of the torque is order of magnitudes larger than in any other anisotropic materials existing in nature.

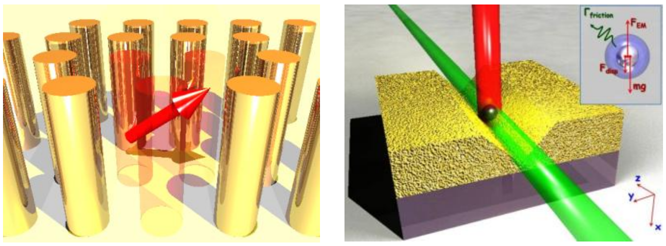

Fig. 1. (left) Schematics of the radiating dipole situated inside hyperbolic material realized as an infinite array of vertical plasmonic nanorods. (right) Schematics of nano-opto-mechanical modulator: a nanoparticle in the V-grove waveguide is driven into oscillatory motion by control beam (red). The particle moves in and out of the fundamental mode of the waveguide (green) and modulates modal loss. Inset shows the forces acting on a nano-object inside the V-groove.

Other interesting opto-mechanical phenomenon that will be discussed in this contribution relies on sub-diffractional confinement of guided plasmonic modes and the ability to enhance and engineer forces on nano-scale. Here we propose and demonstrate the concept of force-induced nonlinear optical interactions [7]. In general light beams of different frequencies cannot interact directly, however they could if a mediating material object is present. Nonlinear materials are commonly used for this purpose. Here we propose a new approach to control light with light, based on a nano-opto-mechanical system integrated in a plasmonic waveguide is proposed. Opto-mechanical motion of a free-floating resonant nanoparticle in a subwavelength plasmonic V-groove waveguide is used of the ptothotype. It is shown that nanoparticle auto-oscillations in the waveguide induced by a control light result in the periodic modulation of a transmitted plasmonic signal. The modulation depth of 10% per single nanoparticle of 25 nm diameter with the clock frequencies of tens of MHz and the record low energy-per-bit energies of 10^{-18} J is observed. The scheme of the proposed approach is presented on Fig. 2. The efficient modulation and deep-subwavelength dimensions make this nano-optomechanical system of significant interest for opto-electronic and opto-fluidic technologies.

Few recent investigations on opto-mecanical phenomena in plasmonics and metamaterials will be presented as well.

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