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Nanomechanical Functionalities in Photonic Metamaterials

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***Abstract* – We review the exceptional variety of functionalities accessible by design in nanomechanical photonic metamaterials, wherein dynamic reconfiguration of sub-wavelength structure by external stimuli can yield extreme and unusual electro-, magneto-, thermo-, acousto- and nonlinear optical response characteristics.**

I. Introduction

The geometric conformation of metamolecules, and their mutual arrangement, in planar photonic metamaterials manufactured on free-standing elastic nano-membranes can be dynamically, reversibly reconfigured by external stimuli – heat, light, electrical signals, magnetic fields, acoustic vibrations - to achieve optical modulation at high (potentially GHz) frequencies. By engaging a combination of mechanical and optical resonances one may enhance the magnitude of both actuation and optical response in nanostructures driven by few-volt electrical signals, microwatt optical beams or low-intensity acoustic vibrations. Nanomechanical metamaterials can be engineered to exhibit profound electro-, magneto- and acousto-optic switching coefficients applicable in a range of signal modulation and sensing contexts; and to present large effective nonlinearities enabling low-intensity light-by-light modulation and the exploration/exploitation of phenomena (such as optical bistability, electrogyration and optomechanical asymmetry) that are extremely small, rare or non-existent in bulk optical media.

II. Latest developments

In recent work, for example, we have demonstrated that ultrasound vibrations can drive substantive linear and nonlinear changes in the optical properties of nanomechanical metamaterials. The conventional acousto-optic (AO) effect causes small perturbations of refractive index in crystals and glasses, and long (mm) interaction lengths are consequently required for high-contrast modulation of light, inhibiting the miniaturization of AO devices. We have shown, in a metamaterial only 100 nm thick, comprised of a free-standing silicon nitride nanowire array decorated with plasmonic resonators, that ultrasonic vibrations (at frequencies of order 1 MHz) can induce nanowire displacements resulting in up to 73% linear modulation of the metamaterial's near-infrared (1310 nm) reflectivity.

We have shown how opto-mechanically reconfigurable all-dielectric metamaterials can manifest strong transmission asymmetry. Optical nonlinearity (high intensities) and static magnetization (the Faraday effect) are conventionally employed to break the reciprocity of optical transmission through bulk media. The same can also be achieved when propagation is accompanied by polarization or mode conversion, as in chiral metamaterials. We show that resonantly enhanced optical forces in free-standing (nanostructured silicon on silicon nitride) metamaterials can be comparable in magnitude to the elastic restoring forces resulting from nanoscale deformation of such structures. They can be engaged to dynamically, reversibly reconfigure the constituent cells of the metamaterial in a manner that depends upon the direction of light propagation, giving rise to differential mode conversion and transmission asymmetry at low <mW/μm^2 intensities.

We demonstrate a nanostructured photonic metamaterial that exhibits quadratic electrogyration orders of magnitude stronger than has been observed in any natural media. One of the most fascinating properties of chiral molecules is their ability to rotate the polarization state of light and since Faraday's experiments in 1845 it has been known that polarization rotation can be induced or changed by a magnetic field. However, the influence of applied electric field on molecular chirality and associated polarization rotation was only discovered and described in the 1960s, and the effect is extremely small in naturally occurring materials. Giant electrogyration is achieved in a metamaterial only 150 nm thick by engaging electrostatic forces to dynamically change the nanoscale chiral configuration of the metamaterial's building blocks, providing a 16° range of azimuth rotation and a 9° range of ellipticity angle change for transmitted near-infrared light.

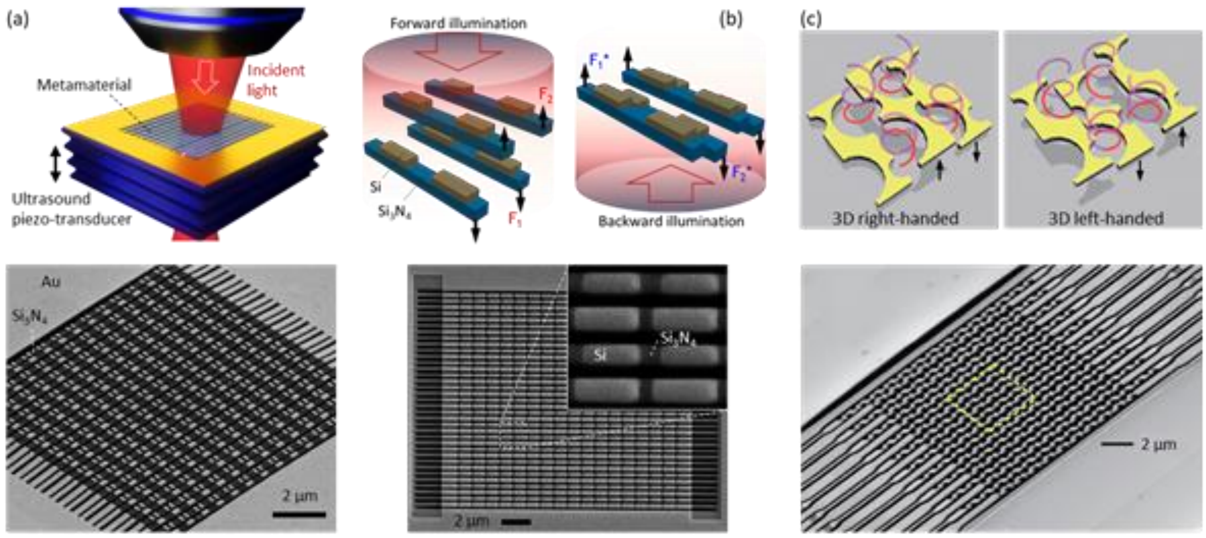

Fig. 1. Nanomechanical photonic metamaterials. (a) Acoustically-driven photonic (plasmonic) metamaterial, (b) Opto-mechanically asymmetric all-dielectric metamaterial. (c) Electro-optic switchably chiral plasmonic metasurface manifesting giant electrogyration.

III. Conclusion

Metamaterials provide a unique platform for manipulating light-matter interactions. By exploiting technological and manufacturing opportunities provided by semiconductor membrane technology they merge concepts of nanophotonics and nanomechanics to present considerable potential for reconfigurable and tunable nanophotonic devices, and novel photonic functionalities

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