Nano-Opto-Mechanical Nonlinear Plasmonic Metamaterials

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Abstract: We demonstrate megahertz-bandwidth modulation of light with light at the milliwatt power level with nano-optomechanical metamaterials fabricated on a nanoscale elastic silicon nitride membrane. The origin of nonlinearity is in the light-induced electromagnetic near-field forces.

The development of nanophotonics towards extreme miniaturization of optical functional elements ultimately aims at the realization of integrated devices consisting of a single optical chip. To reach this goal, novel tools must be developed to manipulate light with light in small areas and interaction lengths. Here we experimentally demonstrate optically driven mechanically reconfigurable photonic metamaterial exhibiting an exceptionally large optical nonlinearity. With nonlinear absorption of $\beta \sim 10^{-2}$ m/W, the nanostructure is 7 orders of magnitude more nonlinear than nonlinear semiconductors such as *GaAs* at optical frequencies.

Fig. 1(a) shows a nonlinear reconfigurable array of Π-shaped plasmonic resonators fabricated by focused ion beam milling from a 50 nm thick gold layer covering a 50 nm thick silicon nitride membrane. In order to optomechanically modulate the metamaterial's optical properties, we pumped the nanostructure with a modulated laser beam at 1550 nm, where simulations predict significant relative optical forces on the bridges. The modulation of the metamaterial's transmission was probed at 1310 nm and detected using a lock-in amplifier. At modulation frequencies of 10s of kHz, the optical pump leads to pronounced modulation of the structure's transmission characteristics at the probe wavelength, see Fig. 1(b). For a pump power of 0.66 mW (peak intensity I =250 W/cm^2) a modulation amplitude on the order of 1% is detected at 25 kHz modulation. As the modulation frequency increases, the out-of-plane and in-plane mechanical resonances are observed optically. While optically induced differential thermal expansion contributes to the mechanical nonlinearity at low frequencies, the in-plane mechanical modes (1 MHz and 1.4 MHz) cannot be directly excited by thermal effects but can be explained by near field optical forces.

In summary, optically driven reconfigurable photonic metamaterials offer an opportunity to achieve precise control over metamaterial properties through optically induced mechanical deformation of nanoscale metamaterial structures by electromagnetic near-field interaction and thermo-optical effects. With light intensity of few μW/μm^2, metamaterial arrays can be sufficiently reconfigured leading to light-by-light modulation with MHz bandwidth.

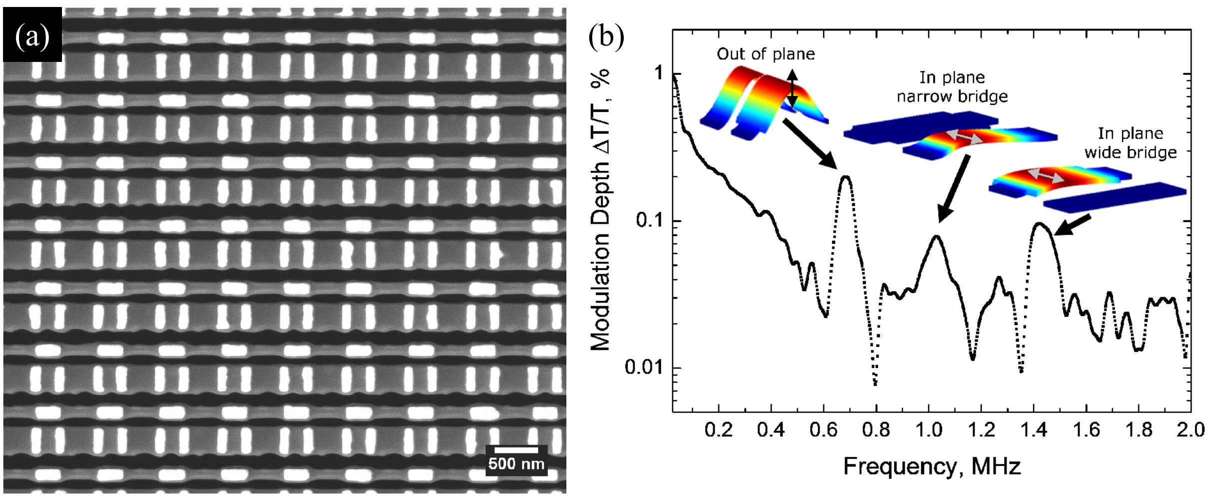

Fig.1: Optically reconfigurable photonic metamaterial. (a) SEM micrograph of the metamaterial consisting of a Π-shaped gold resonators fabricated by focused ion beam milling on a free standing silicon nitride membrane. (b) Modulation depth as a function of modulation frequency for a pump power of 0.66 mW on a logarithmic scale, where simulations of the mechanical eigenmodes are shown as insets.