Tuneable Metamaterials Driven by Light

Jun-Yu Ou[1], Eric Plum[1], Nikolay I. Zheludev[1,2]

1. Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, Southampton SO17 1BJ, United Kingdom

2. Centre for Disruptive Photonic Technologies, Nanyang Technological University, Singapore 637378, Singapore

All-optical data processing fundamentally relies on giant optical nonlinearities to enable high-contrast modulation of light with light at low power levels in highly integrated systems with short interaction lengths. Here we demonstrate optically driven mechanically reconfigurable nanostructures exhibiting exceptionally large optical nonlinearities. Nano-opto-mechanical nonlinear materials that are 7 orders of magnitude more nonlinear than GaAs achieve several percent intensity modulation at 2 mW power with an interaction length of less than 1/10 of a wavelength.

Fig. 1(a) shows a nano-opto-mechanical nonlinear metamaterial consisting of Π-shaped plasmonic resonators supported by silicon nitride bridges fabricated by focused ion beam milling from a 50 nm thick gold layer covering a 50 nm thick silicon nitride membrane. The nanostructure can be reconfigured by light due to (i) optical forces associated with excitation of its plasmonic resonances [1, 2] and (ii) differential thermal expansion of gold and silicon nitride in response to optical heating. Fig. 1(b) shows the measured modulation of the nanostructure's transmission at a probe wavelength of 1310 nm in response to illumination with a modulated pump beam at 1550 nm. At modulation frequencies of 10s of kHz, the optical pump modulates the structure's transmission characteristics at the probe wavelength. For a pump power of 2 mW (peak intensity I =206 W/cm^2) a modulation amplitude on the order of 1% is detected at 25 kHz. As the modulation frequency increases, pronounced transmission modulation reaching several percent is observed at the out-of-plane and in-plane mechanical resonances of the bridge beams. The observed nonlinearity corresponds to a nonlinear absorption coefficient on the order of 10^{-2} m/W (compared to 3x 10^{-10} m/W for GaAs). While optically induced differential thermal expansion contributes to the mechanical nonlinearity at low frequencies, the excitation of in-plane mechanical modes (1.2 MHz and 1.4 MHz) cannot be excited directly by thermal effects but can be explained by near field optical forces.

In summary, optically actuated tuneable metamaterials offer an opportunity to achieve giant optical nonlinearities and precise control over metamaterial properties through optically induced mechanical deformation of nanoscale metamaterial structures by electromagnetic near-field interactions and thermo-optical effects. With light intensities of few μW/μm^2 metamaterial arrays can be sufficiently actuated to modulate light by light with MHz bandwidth.

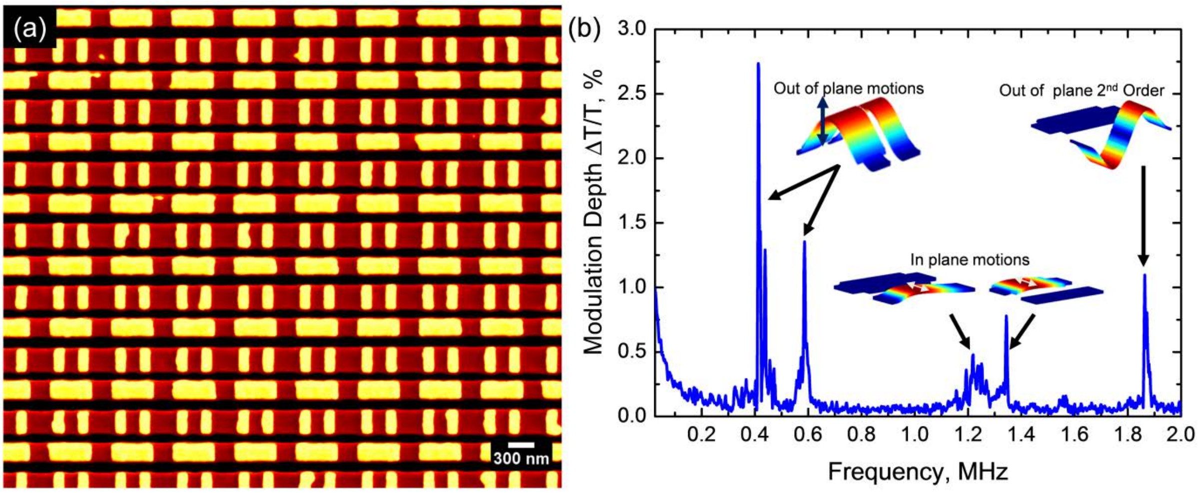

Fig. 1.: Optically reconfigurable photonic metamaterial. (a) Scanning electron microscope image with false colours showing an optically reconfigurable metamaterial nanostructure consisting of gold (yellow) plasmonic resonators supported by free-standing silicon nitride bridges (red). (b) Modulation depth as a function of modulation frequency for a pump power of 2 mW. The simulated mechanical eigenmodes are shown as insets.

References

[1] J. Zhang, K. F. MacDonald, and N. I. Zheludev, "Optical gecko toe: optically controlled attractive near-field forces between plasmonic metamaterials and dielectric or metal surfaces" Phys. Rev. B 85, 205123 (2012).

[2] V. Ginis, P. Tassin, C. M. Soukoulis, I. Veretennicoff, "Enhancing Optical Gradient Forces with Metamaterials" Phys. Rev. Lett. 110(5), 057401(2013)