Controlling Light with Light in Nano-Opto-Mechanical Metamaterial

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***Abstract* – We demonstrate nano-opto-mechanical metamaterial with a cubic optical nonlinearity that is seven orders of magnitude greater than the reference nonlinearity of GaAs. The nonlinearity is driven by light-induced deformation of the plasmonic nanostructure.**

I. INTRODUCTION

The force exerted by photons is of fundamental importance in light-matter interactions. This optical force is greatly enhanced in photonic nanostructures where light is concentrated at the nanoscale [1, 2]. Here, we exploit opto-thermal and optical forces to demonstrate control of light with light in a plasmonic metamaterial experimentally. At the nanoscale, light-driven electromagnetic near-field interactions and thermo-optical effects can compete with elastic forces. Light intensities of only a kW/cm^2 reconfigure the metamaterial array of plasmonic metamolecules fabricated on a flexible substrate leading to a significant change of its optical properties. This new type of nonlinearity has a resonant character and can provide modulation of light by light at kHz and MHz frequencies.

II. NANO-OPTO-MECHANICAL NONLINEARITY

The optomechanical photonic metamaterial studied here is based on a Π-shaped resonator design, see Fig. 1. In order to allow mechanical deformation of the plasmonic Π meta-molecules, the horizontal and vertical bars have been supported by different flexible dielectric bridges. The nanostructures were fabricated by focused ion beam milling from a 50 nm thick silicon nitride membrane covered with a 50 nm thick thermally evaporated layer of gold.

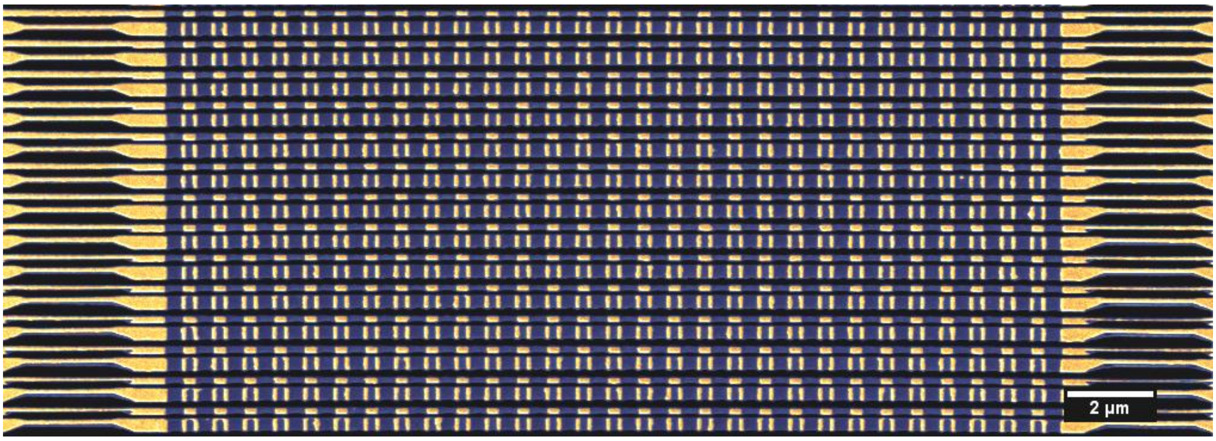

Fig.1 Optically reconfigurable photonic metamaterial. Scanning electron microscope image of the nanostructure consisting of gold (yellow) plasmonic resonators supported by free-standing silicon nitride bridges (blue).

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. For a pump power of 0.9 mW (peak intensity I =1 kW/cm^2) a modulation amplitude on the order of 1% is detected at 25 kHz modulation, see Fig. 2. As the modulation frequency increases, resonant transmission modulation associated with the out-of-plane and in-plane mechanical resonances of the bridges is observed. While optically induced differential thermal expansion contributes to the mechanical nonlinearity at low frequencies, the in-plane mechanical modes at 1 MHz and 2 MHz cannot be directly excited by thermal effects but can be explained by near field optical forces, see insets of Fig. 2.

The transmission modulation depends linearly on the pump intensity and can therefore be described by the first nonlinear absorption coefficient β. Assuming that the nonlinear transmission change ΔT results from nonlinear absorption, $\beta \sim \Delta T/(It)$, where I is the intensity and t is the metamaterial thickness. For 25 kHz modulation, $\beta \sim 10^{-3}$ m/W, which exceeds the nonlinearity of the classic nonlinear reference medium of GaAs by about 7 orders of magnitude [3].

III. Conclusion

Nano-opto-mechanical metamaterials offer an opportunity to achieve precise control over metamaterial properties through optically induced mechanical deformation of nanoscale metamaterial structures by electromagnetic near-field interactions and thermo-optical effects. Giant nano-opto-mechanical nonlinearities allow the modulation of light with light at intensities of only kW/cm^2.

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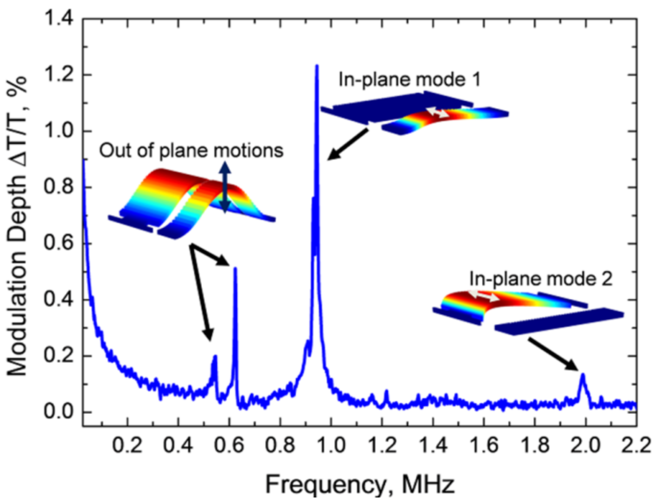

Fig.2 Modulation depth as a function of modulation frequency for a pump power of 0.9 mW. Simulations of the mechanical eigenmodes are shown as insets.

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] Wiederhecker, Gustavo S., Long Chen, Alexander Gondarenko, and Michal Lipson. "Controlling photonic structures using optical forces." Nature 462, no. 7273 (2009): 633-636.

[3] Said, A. A., Mansoor Sheik-Bahae, David J. Hagan, T. H. Wei, J. Wang, James Young, and Eric W. Van Stryland. "Determination of bound-electronic and free-carrier nonlinearities in ZnSe, GaAs, CdTe, and ZnTe." JOSA B 9, no. 3 (1992): 405-414.