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Optomechanical Guitar: Reconfiguring Metamaterials with Sub-wavelength Spatial Resolution

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Abstract: **Optomechanical metamaterials, where optical signals actuate unique elements of the nanostructure at their eigenfrequency, can be used to modulate metamaterials with sub-wavelength spatial resolution. We demonstrate the first all-optically addressable metadevice operating in the near-infrared.**

I. INTRODUCTION

Metamaterials provide novel functionalities by engineering electromagnetic space and controlling propagation of waves [1], however, these are typically fixed by the physical design of the metamaterial structure. Here we tackle this issue with optically addressable metamaterials in order to obtain optical properties on demand in space and time. In such a device, optically-induced forces drive structural reconfiguration which controls the near-field coupling between resonators and thus the local optical properties [2]. Spatial addressing within the metamaterial is realized by controlling the mechanical eigenfrequencies of the nanostructure. This approach enables all-optical dynamic control over intensity and phase of light with sub-wavelength spatial resolution.

II. ADDRESSING METAMATERIAL WITH LIGHT

The optomechanical photonic metamaterial studied here is based on a Π-shaped plasmonic resonator design supported by silicon nitride bridges. The structure was fabricated by focused ion beam milling from a 50 nm thick gold layer covering a 50 nm thick silicon nitride membrane, see Fig. 1. In order to create individual bridge

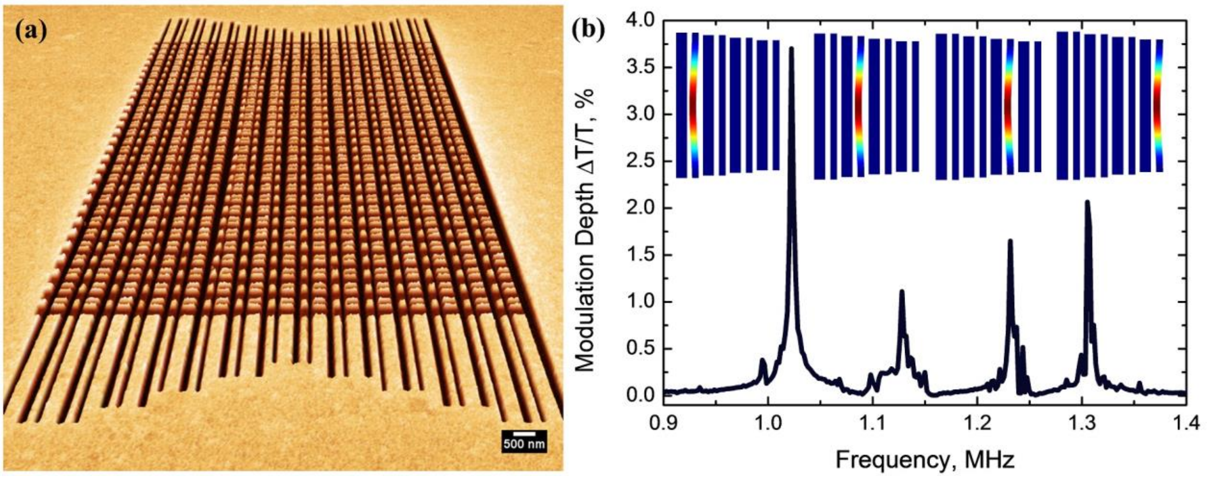

Fig. 1. Optically addressable reconfigurable photonic metamaterial.(a) 3D Scanning electron microscope image with false colours showing the optically reconfigurable metamaterial nanostructure consisting of gold (yellow) plasmonic resonators supported by free-standing silicon nitride bridges (brown). The unit cell size is 700 nm x 700 nm. (b) Probe modulation depth as a function of pump modulation frequency for a pump power of 225 μW (intensity of 245 W/cm^2), pump wavelength 1550 nm and probe wavelength 1310 nm. The inset shows simulations of the in-plane mechanical modes corresponding to the transmission modulation peaks of the nanostructure. The pump and probe beams are polarized parallel to the bridges.

pairs with unique mechanical eigenfrequencies that could be addressed through a modulated optical signal, the length of the supporting bridges is varied from 28μm to 24μm.

The metamaterial can be actuated by light due to (i) optical forces associated with excitation of its plasmonic resonances and (ii) differential thermal expansion of gold and silicon nitride in response to optical heating. Maxwell stress tensor calculations show optical forces acting on the Π-resonators around their 1240 nm absorption resonance, see Fig. 2(a) and (b). As the normally incident photons only carry momentum along the *z*-direction, there cannot be any net in-plane optical forces on the unit cell, $F_{y1} + F_{y2} = 0$. In close agreement with this relationship, our simulations show substantial relative optical forces acting on different components of the unit cell. The relative optical forces F_{y2}-F_{y1} between the unit cell's bridge segments reach about 0.4 P/c, where *P* is the incident power per unit cell and *c* is the speed of light in vacuum.

Measurements of the nanostructure's transmission modulation at a probe wavelength of 1310 nm in response to illumination with a modulated pump beam at 1550 nm show non-resonant low frequency modulation and resonant high frequency modulation. At low modulation frequencies of 10s of kHz, the optical pump modulates the structure's transmission characteristics at the probe wavelength without engaging mechanical resonances. For a pump power of 225 μW (peak intensity I =245 W/cm^2) a modulation amplitude on the order of 0.5% is detected at 25 kHz. As the modulation frequency increases, four pronounced transmission modulation peaks reaching modulation depths of a few percent are observed corresponding to the in-plane mechanical resonances of the bridge beams of different lengths see Fig. 1(b).

As the bridge pairs have different mechanical resonance frequencies, their mechanical oscillation can be controlled independently by the optical pump beam, which can be modulated at a combination of resonance frequencies that can also be amplitude modulated. Here, the spatial resolution is given by the bridge pair width of 700 nm. This resolution is substantially subwavelength in comparison to both the pump and probe wavelength.

A recent demonstration of optical actuation of optomechanical metamolecules suggests that metamaterials allowing targeted optical actuation of every individual metamolecule should be possible [3]. The prescribed structural reconfiguration of the metamolecules then modulates amplitude and phase of transmitted/reflected electromagnetic waves with sub-wavelength resolution, providing means for arbitrary temporal and spatial modulation of optical wave fronts.

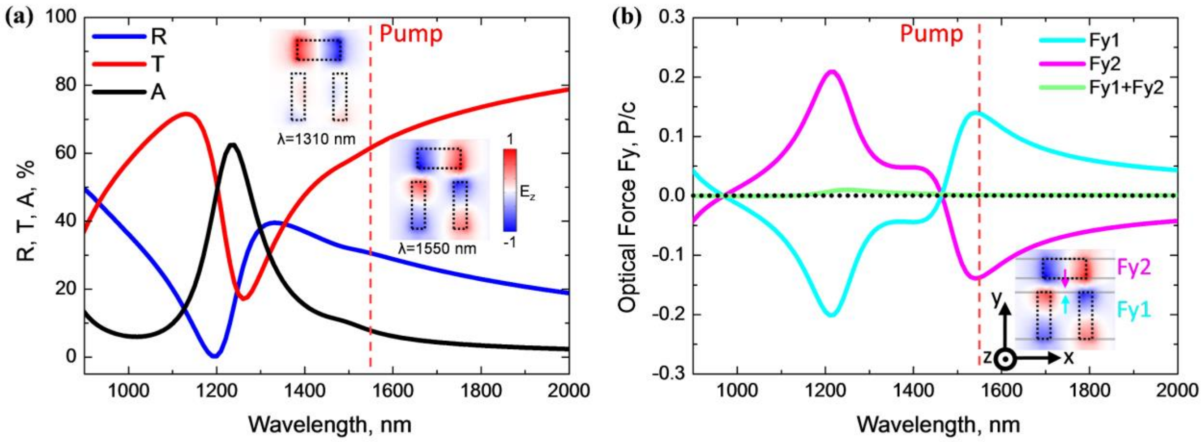

Fig. 2. Calculated optical spectra and optical forces. (a) Simulated metamaterial transmission T, refection R and absorption A spectra. Insets show maps of the optically induced charge distributions at the probe (1310 nm) and pump (1550 nm) wavelengths in terms of the instantaneous electric field E_z that these charges generate normal to the metamaterial surface. The maps are normalized to the maximum of E_z. (b) In-plane-of-metamaterial component of optical forces $F_{y1,2}$ acting between the strip segments of an individual unit cell according to Maxwell stress tensor calculations. Dashed lines indicate the 1550 nm optical pump wavelength. The incident radiation is polarized with the electric field parallel to the strips in all cases.

VI. Conclusion

Our experimental results show that optically addressable metamaterials enable simultaneous spatial and temporal modulation of optical properties, taking photonic metamaterials to the next level of functionality. We demonstrate modulation of metamaterial transmission at standard telecommunications wavelengths with sub-wavelength spatial resolution in one dimension. We argue that such sub-wavelength resolution spatial light modulators can also be realized with two-dimensional optical addressing of individual optomechanical metamolecules as well as selective modulation of intensity and phase of light.

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