Playing a Metamaterial Guitar with Light: Optically Addressable Optomechanical Metamaterial

Jun-Yu Ou[1], Eric Plum[1], B. Clarke[1], and Nikolay I. Zheludev[1, 2]
[1]Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, SO17 1BJ, UK
[2]Centre for Disruptive Photonic Technologies and The Photonics Institute, Nanyang Technological University, Singapore 637371, Singapore
Author e-mail address: bruce.ou@soton.ac.uk

Abstract: Optical signals actuating unique elements of a nanostructure at their eigenfrequencies are used to modulate metasurface properties with sub-wavelength spatial resolution thus creating a randomly addressable metamaterial that acts as all-optical spatial light modulator.

OCIS codes: (160.3918) Metamaterials; (190.0190) Nonlinear optics; (310.6628) Sub-wavelength structures, nanostructures; (120.4880) Optomechanics

1. Introduction

Metamaterials are a paradigm for engineering electromagnetic space and controlling propagation of waves. They provide a plethora of novel functionalities, however, these are typically narrowband and fixed. 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. Spatial addressing within the metamaterial is realized by controlling the mechanical eigenfrequencies of the nanostructure. This approach enables dynamic control over intensity and phase of light by light.

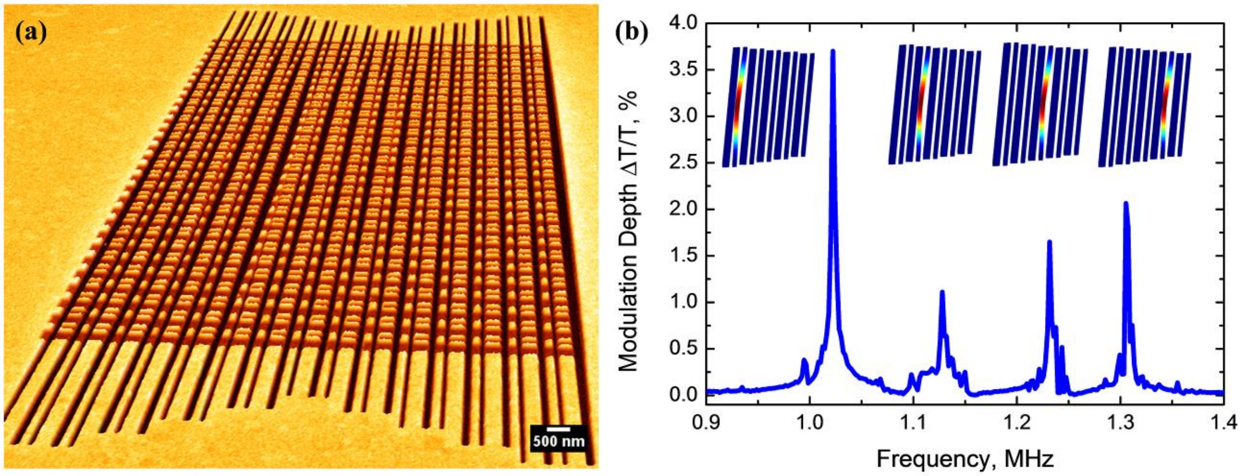

Fig. 1. Optically addressable reconfigurable photonic metamaterial. (a) 3D Scanning electron microscope image with false colours showing the optically reconfigurable metamaterial nanostructure consisting of gold (yellow) plasmonic resonators supported by free-standing silicon nitride bridges (brown). 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.

2. Results

Fig. 1(a) shows an optomechanical 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. In order to create individual bridge pairs with unique eigenfrequencies that could be addressed through a modulated optical signal, the length of supporting bridges is varied from 28μm to 24μm.

The nanostructure can be reconfigured 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 reveal 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_2-F_1 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 width of a bridge pair that is 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. The prescribed structural reconfiguration of the metamolecules then modulates amplitude and phase of transmitted/reflected electromagnetic waves with sub-wavelength resolution, providing means for creating arbitrary wave fronts in time and space.

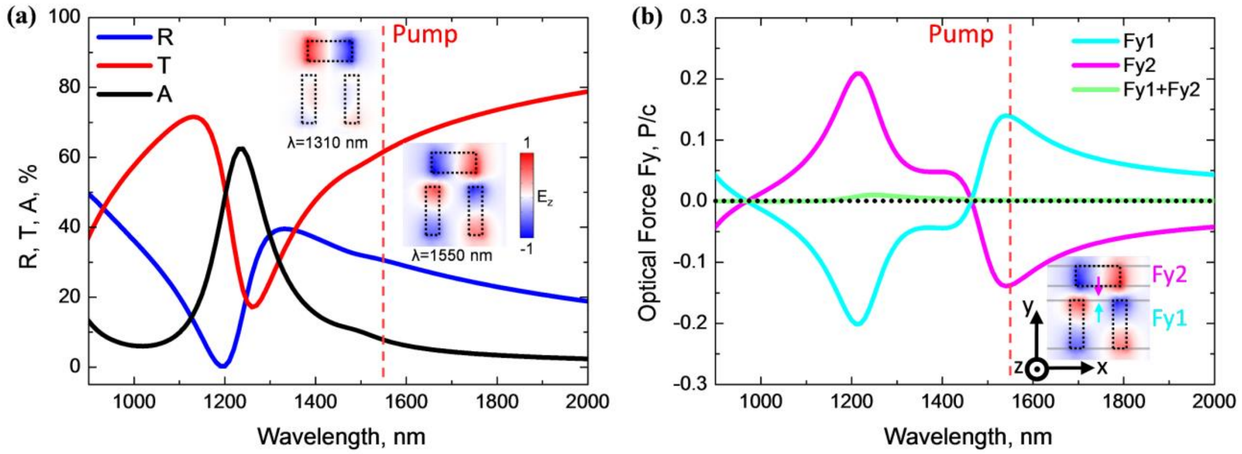

Fig. 2. Optical spectra and optical forces. (a) Simulated metamaterial transmission T, refection R and absorption A spectra. Insets show maps of the optically induced charge distributions at the probe (1310nm) and pump (1550nm) wavelengths in terms of the instantaneous electric field E_z that these charges 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.

3. Summary

In summary, we demonstrate that optically addressable metamaterial enables simultaneous spatial and temporal modulation of optical properties, taking photonic metamaterials to the next level of functionality. 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.