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Optical metamaterial reconfigured with sound

D. Papas [1], J. Y. Ou [1], E. Plum[1], N. I. Zheludev[1,2]

[1] Optoelectronics Research Centre & Centre for Photonic Metamaterials, University of Southampton, Southampton, SO17 1BJ, UK
[2] Centre for Disruptive Photonic Technologies, SPMS, TPI, Nanyang Technological University, Singapore 637371, Singapore
D.Papas@soton.ac.uk

***Abstract* – We demonstrate that ultrasound vibrations cause linear and nonlinear changes of optical properties of nanomechanical metamaterials that are comparable to the magnitude of the optical properties themselves. We observe up to 73% linear acousto-optical reflectivity modulation in a metamaterial of only 100 nm thickness and substantial nonlinear acousto-optical modulation up to the sixth order. Our results indicate that acousto-optical metamaterials enable the miniaturization of acousto-optical technology by orders of magnitude and acousto-optics with extreme nonlinearity.**

I. INTRODUCTION

The modulation of optical properties by sound is known as the acousto-optical effect, which causes small refractive index perturbations with negligible nonlinearity in crystals and glasses. Interaction lengths of millimeters are required for high-contrast modulation of light and prevent the miniaturization of conventional acousto-optical technology.

We argue that true miniaturization of acousto-optics and large nonlinearities require complete rearrangement of the material structure by acoustic vibrations, as in phase transitions rather than perturbations. Here we demonstrate giant linear and nonlinear modulation of the reflectivity of a nanomechanical metamaterial that is rearranged by ultrasound vibrations.

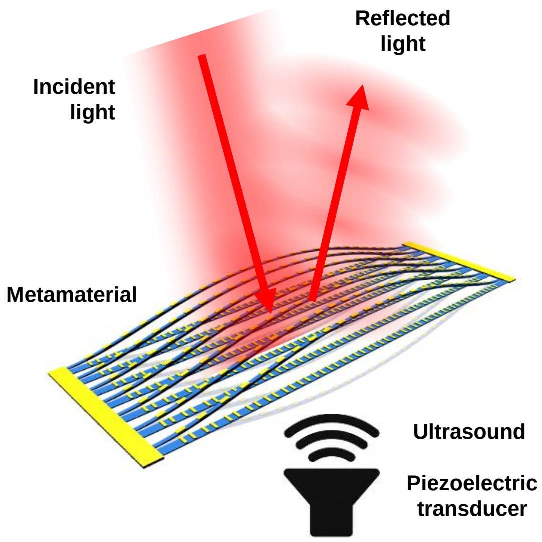

Fig. 1. Modulating metamaterial optical properties with sound. A piezoelectric transducer generates ultrasound vibrations that drive out-of-plane oscillations of nanowires supporting a photonic metamaterial, resulting in large linear and nonlinear modulation of the metamaterial's reflectivity.

II. RESULTS

The metamaterial is a periodic arrangement of coupled plasmonic resonators supported by alternating nanowires with different mechanical resonance frequencies (Fig. 1). Vibration of the nanowires causes relative displacement of the coupled plasmonic resonators and therefore modulates the nanostructure's optical properties. We drive ultrasound frequency vibrations of the acousto-optical metamaterial using a piezoelectric transducer and observe the resulting modulation of its reflectivity.

The metamaterial nanostructure was fabricated by focused ion beam milling from a gold-coated silicon nitride membrane. It consists of Π-shaped arrangements of 50-nm-thick gold bars with a period of 700 nm (Fig. 2a). The plasmonic unit cells are supported by pairs of freestanding 50-nm-thick silicon nitride nanowires of 19 μm length to enable relative movement of the electromagnetically-coupled gold bars. The metamaterial structure has near-infrared absorption resonances at wavelengths of about 800 nm and 1200 nm and its optical properties have a strong spectral dependence near these resonances.

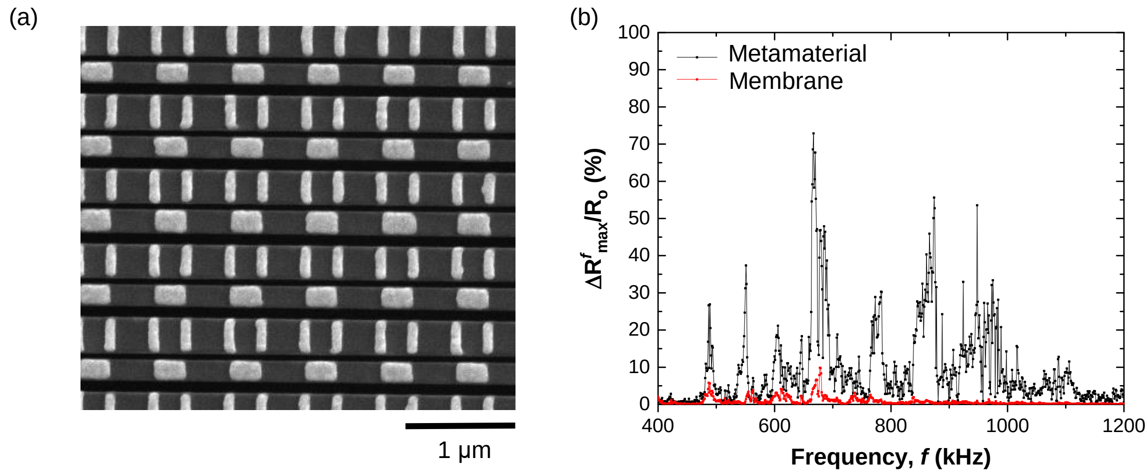

Fig. 2 Acoustic modulation of metamaterial reflectivity. (a) SEM image of the nanomechanical metamaterial array. (b) Reflectivity modulation of the metamaterial and the unstructured membrane at the mechanical vibration frequency *f* measured at 1310 nm wavelength.

Piezoelectric vibration of the metamaterial nanostructure causes up to 73% linear modulation of its reflectivity at a wavelength of 1310 nm (Fig. 2b). This is the peak-to-peak amplitude of reflectivity modulation at the piezoelectric actuation frequency *f*, i.e. it corresponds to the linear component of acousto-optical modulation and, assuming sinusoidal displacement of the nanostructure, it arises from the linear component of reflectivity change with displacement. The reflectivity modulation has a complex frequency dependence with many resonant maxima associated with mechanical resonances of the coupled system of piezoelectric transducer, membrane and 34 nanowire oscillators. Reference measurements (red) on an unstructured part of the gold-coated membrane hosting the metamaterial reveal resonances of membrane and piezoelectric transducer that cause weak modulation due to deflection of reflected light. Comparison indicates that resonances below 800 kHz are mainly caused by resonant oscillation of membrane and transducer, while resonances above 800 kHz are due to the fundamental mechanical resonances of the metamaterial's 34 nanowires, which is consistent with mechanical eigenfrequency simulations.

Linear approximations are appropriate for describing small changes in optical properties caused by small deformations (perturbations). Mechanical rearrangements of a metamaterial structure causing 73% changes of its optical properties are clearly outside the perturbative regime of conventional acousto-optics and therefore substantial nonlinear effects may be expected. Fig. 3a shows the time-dependent reflectivity oscillation of the metamaterial during piezoelectric actuation at 665 kHz with sinusoidal actuation voltages of 1V and 5V peak-to-peak amplitude. At this frequency the piezoelectric transducer is resonant and drives large forced oscillations of the metamaterial structure. At 1V, the sinusoidal mechanical oscillation of the nanostructure causes a sinusoidal reflectivity modulation with clear nonlinear distortions. The nonlinear distortions increase and the average reflectivity decreases as the actuation voltage is increased to 5V. The nature of the nonlinear acousto-optical reflectivity modulation becomes clear from the Fourier transform of the time-dependent reflectivity traces (Fig. 3b). While linear acousto-optical modulation dominates at low voltages, linear and nonlinear acousto-optical modulation become comparable as the actuation voltage increases. At 5V, 37% linear acousto-optical modulation is accompanied by 29% second-order, 24% third-order, 18% fourth-order, 5% fifth-order and 4% sixth-order nonlinear acousto-optical modulation.

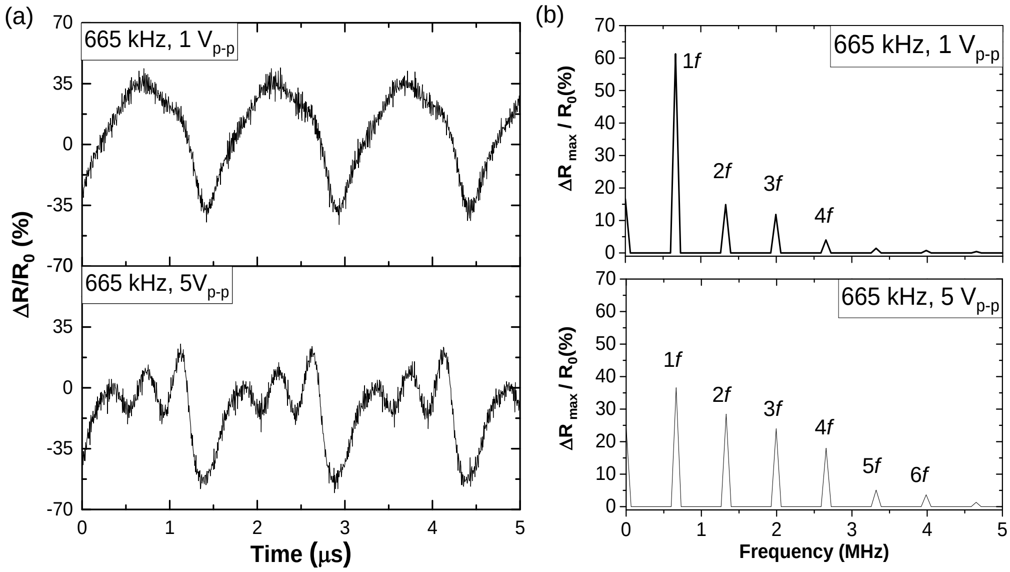

Fig. 3 Nonlinear acoustic modulation of metamaterial reflectivity. (a) Relative reflectivity change at 1310 nm wavelength as a function of time for different amplitudes of sinusoidal piezoelectric actuation 665 kHz. (b) Acousto-optical reflectivity modulation amplitudes (peak-to-peak) at the frequency of mechanical vibration (*f*) and its harmonics obtained by Fourier transform of the data in (a).

III. Conclusion

In summary, we demonstrate exceptionally large linear and nonlinear acousto-optical modulation of optical properties of nanomechanical metamaterials. We observe up to 73% linear modulation of metamaterial reflectivity and up to sixth-order nonlinear reflectivity modulation driven by vibration of the nanostructure at ultrasound frequencies. We argue that nanomechanical metamaterials enable drastic miniaturization of acousto-optical devices and acousto-optics with extreme nonlinearity.

Acknowledgement

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