Acoustically driven photonic metamaterials

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Abstract: We modulate the optical properties of nanomechanical reconfigurable metamaterials with ultrasound. Resonant vibration of the elements of the metamaterial array leads to pronounced changes in its optical properties.

We demonstrate control over the optical properties of nanomechanical metamaterials with ultrasound, which has the potential to deliver both large modulation amplitudes and control over individual nanomechanical oscillators in large arrays. These properties are not available from existing nanomechanical metamaterials, but they are essential for the development of reconfigurable metamaterials with independent dynamic control over the optical properties of every element, which is arguably the ultimate vision behind reconfigurable metamaterials.

Acousto-optical modulation is observed in a nanomechanical metamaterial mounted on a piezoelectric source of ultrasound frequency vibrations (Fig. 1a). The metamaterial array consists of Π-shaped gold resonators of 700 nm period supported by silicon nitride nanowires of 50 nm thickness and 19 μm length (Fig. 1b inset). The metamaterial was fabricated by focused ion beam milling on a gold-coated silicon nitride membrane and its optical properties are controlled by the Π-shaped resonators, while its mechanical properties are controlled by the nanowires. The nanostructure has infrared optical resonances and mechanical resonances at ultrasound frequencies close to 1 MHz. Fig. 1b shows the reflectivity modulation of the metamaterial (black) and an unstructured part of the same gold-coated membrane (red) resulting from 100 kHz-1.2 MHz ultrasound vibrations. The vibrations were generated by driving the piezoelectric ultrasound source with a 1 $V_{p\text{-}p}$ sinusoidal voltage and the resulting modulation of a 1310 nm wavelength CW laser beam was detected with a lock-in amplifier. The metamaterial's reflectivity modulation reaches up to 11% and exhibits a range of resonances. Below 800 kHz, resonant reflectivity modulation of metamaterial and unstructured membrane typically coincide, indicating that it is due to mechanical modes of the membrane that hosts the metamaterial. Above 800 kHz, strong modulation of the metamaterial's reflectivity coincides with negligible reflectivity modulation of the unstructured membrane, indicating that the modulation arises from the fundamental mechanical resonances of the metamaterial nanowires, which is consistent with simulations. The modulation of the metamaterial's optical properties is caused by relative motion of its horizontal and vertical gold bars. Further experiments show that in addition to reflectivity modulation at the acoustic oscillation frequency, also the metamaterial's time-averaged reflectivity can be controlled. Acousto-optical modulation of the metamaterial's average reflectivity is observed throughout the 1000 to 2000 nm wavelength range at mechanical resonance frequencies. For example, the metamaterial's time-averaged reflectivity can be increased by almost 10% at wavelengths around 1900 nm by driving the ultrasound source with 5 $V_{p\text{-}p}$ at the metamaterial's 865 kHz resonance.

In summary, our results show that ultrasound can drive large changes of optical properties of nanomechanical metamaterials. Use of nanomechanical oscillators with different resonance frequencies, such as nanowires of slightly different length, will enable selective actuation of individual nanomechanical metamaterial elements.

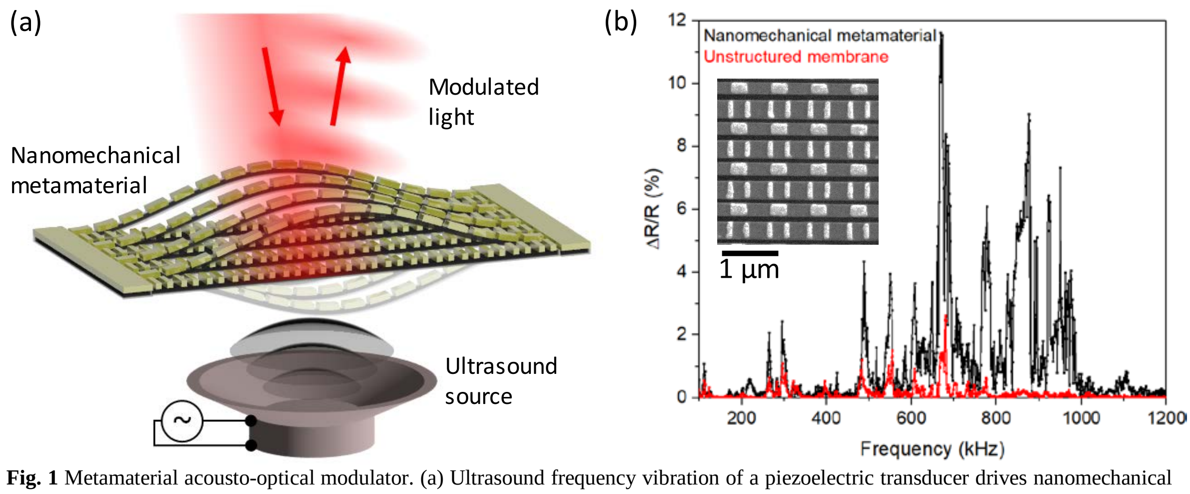

Fig. 1 Metamaterial acousto-optical modulator. (a) Ultrasound frequency vibration of a piezoelectric transducer drives nanomechanical oscillators making up a reconfigurable metamaterial, resulting in modulation of the metamaterial's reflectivity. (b) Measured reflectivity modulation ΔR/R at 1310 nm wavelength caused by vibrating the metamaterial (black) and a reference sample (red) with the piezoelectric ultrasound source at 1 $V_{p\text{-}p}$ across a wide range of ultrasound frequencies. The inset shows part of the nanomechanical metamaterial consisting of gold plasmonic resonators (light gray) supported by freestanding silicon nitride nanowires of 19 μm length (dark gray).