Experimental Observations of Thermal Fluctuations of Metamaterial Optical Properties

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Abstract: We demonstrate that fluctuations in the optical properties of nanomechanical photonic metamaterials can reach 1% at room temperature. Such fluctuations arise from 'Brownian' motion and peak at the frequencies of the nanostructures' natural mechanical modes. © 2022 The Authors

Nanomechanical photonic metamaterials optical and mechanical resonances in tandem to engineer giant nonlinear-optical, electro-, magneto-electro-, acousto-optical and even bistable properties. However, nanomechanical structures are subject to thermal vibrations, with amplitudes that can reach 100s of picometers, at megahertz frequencies. These can lead to fluctuations in the optical properties of highly sensitive structures, such as photonic metamaterials. Unlike a Brownian particle in liquid or air, where thermal motion is the result of external collisions with surrounding molecules, for nano-mechanical structures in vacuum, thermal motion is driven internally, by momentum transfer from the annihilation and creation of flexural phonons within the structure. Here we report that high-frequency time-domain fluctuations of the optical transmission and reflection spectra of nanomechanical metamaterials are directly linked to the picometre-scale thermal motion of their components and can provide information on the fundamental mechanical frequencies and damping of the mechanical modes. We demonstrate this by analyzing time-resolved fluctuations in the transmission and reflection of dielectric and plasmonic nanomembrane metamaterials under vacuum at room temperature. These measurements reveal complex mechanical responses, understanding of which is essential for the optimization of such functional photonic materials. The magnitude of observed metamaterial transmission and reflection fluctuations is of order 0.1%, but may exceed 1% at optical resonances.

We consider photonic metamaterials comprising arrays of free-standing nanowire beams (mechanical oscillators) supporting subwavelength optical resonators (Fig. 1). Thermal vibrations – displacements between neighboring beams of picometric amplitude (maximized at the structure's natural mechanical frequencies) – lead to modulations of reflected and/or transmitted light, which present as sharp peaks in reflection/transmission frequency spectra (Fig. 2).

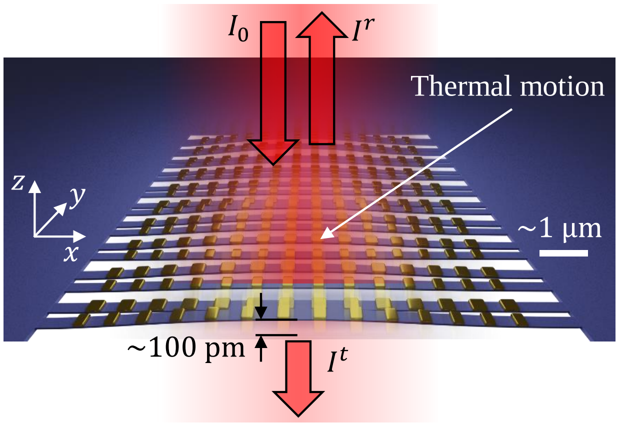

Fig. 1. Fluctuations of nanomechanical metamaterial optical properties due to thermal motion. In an ensemble of nanowires (mechanical oscillators) supporting a periodic array of subwavelength optical resonators, picometric thermal vibrations of individual nanowires modulate the optical properties of the array.

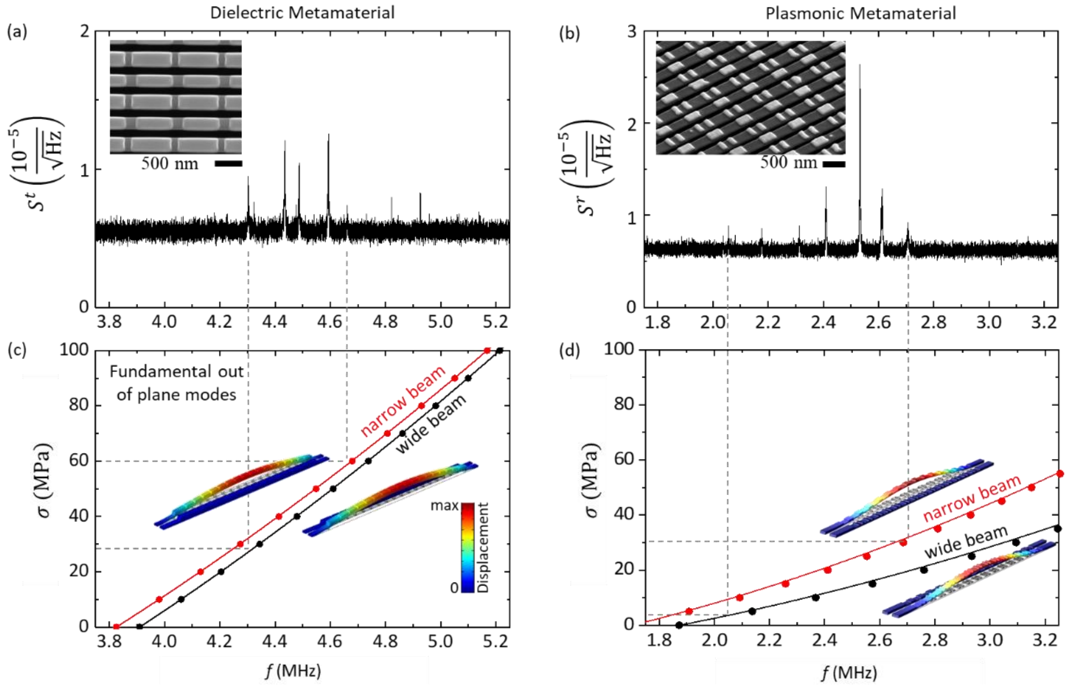

Fig. 2. Figure 4. Thermal fluctuation in the optical properties of nanomechanical metamaterials. (a, b) Measured spectral density of (a) transmission modulation S^t at a wavelength of 1550 nm and (b) reflectance modulation S^r at 1310 nm by, respectively, all-dielectric and plasmonic metamaterials. Insets show scanning electron micrographs of sections of the metamaterials. (c, d) Numerically simulated dependences on tensile stress σ of fundamental frequencies f of the out-of-plane flexural modes of the nanowire elements from which the (c) dielectric and (d) plasmonic metamaterials are constructed.

We experimentally study reflectance S^r and transmittance S^t modulation due to thermal motion in both plasmonic and dielectric nanomechanical photonic metamaterials. The inset to Fig. 2a shows an all-dielectric metamaterial fabricated on a 200 nm thick silicon nitride membrane coated with 115 nm of amorphous silicon. This bilayer was then structured by focused ion beam milling to define an array of asymmetric nanorod pairs in the amorphous silicon layer, on 20.3 μm long silicon nitride beams. Figure 2a shows the frequency spectrum of metamaterial transmission: sharp peaks correspond to the thermal motion of individual beams. Their displacement amplitudes are of order 50 pm, and lead to near-infrared transmission fluctuations of ~0.05%. The inset to Fig. 2b shows a plasmonic metamaterial consisting of 14 μm long silicon nitride beams supporting plasmonic optical resonators fabricated, on a 50 nm thick silicon nitride membrane coated with 50 nm gold, again by focused ion beam milling. Figure 2b shows the frequency spectrum of metamaterial reflection. Thermal motion displacement amplitudes in this case are ~160 pm, leading to reflectivity fluctuations of ~0.1%. In both cases, metamaterial optical resonances are detuned slightly from the laser wavelengths. Were they to coincide, modulation amplitudes would be higher, reaching ~0.1% in transmission for the dielectric metamaterials and ~1.5% for the plasmonic metamaterial in reflection.

The ability to resolve fluctuations in transmission and reflection related to the thermal motion of individual nanowire beams within the metamaterial ensembles arises from the fact that even nominally identical beams have, in practice, slightly different Eigenfrequencies. This is not principally a consequence of manufacturing imperfections but rather variations in tensile stress over the silicon nitride membrane. Figures 2c and 2d illustrate the relationships between stress and fundamental frequency. Experimentally observed variations in frequency are accounted for by beam-to-beam tensile stress variations of order 30 MPa – a value in keeping with the hundreds of MPa to GPa intrinsic stress values typical of unstructured silicon nitride membranes.

In summary, we demonstrate the detection of phonon-driven fluctuations in the optical properties of nanomechanical metamaterials. Our findings open new opportunities for mechanical characterization of nanostructures and may be applied, for example, to high sensitivity optical detection of mass and temperature variations.