Thermal fluctuations in the optical properties of dielectric and plasmonic nanomechanical metamaterials

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Abstract: We experimentally observe that fluctuations in metamaterial optical properties peak at the frequencies of the nanostructures' natural mechanical modes, due to 'Brownian' motion. Fluctuations in flexural phonon density are the underlying mechanism for this motion, which is observed as fluctuations in optical properties reaching 1% at room temperature.

Nanomechanical structures are subject to thermal vibrations with amplitudes that can reach 100s of picometers, in the megahertz frequency range. They lead to significant fluctuations of 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.

Thermal vibrations modulate the light scattered by a nanomechanical system and this modulation is maximized at the structure's natural mechanical frequencies. In a nanowire array supporting subwavelength optical resonators (Fig. 1a), such vibrations lead to modulation of the reflected and/or transmitted light, which present as sharp peaks in reflection/transmission frequency spectra (Fig. 1b). The signal amplitude spectral density $S^{r,t}(f)$ resulting from small thermomechanical fluctuations is given by: $S^{r,t}(f) = \frac{\delta I^{r,t}/I^{r,t}}{\sqrt{\delta f}} = \frac{1}{\mu_0^{r,t}(\mathrm{F})} \times \frac{\partial \mu^{r,t}(z,\mathrm{F})}{\partial z}\Big|_{z=0} \times \sqrt{\frac{k_B T f_0}{2\pi^3 m_{\mathrm{eff}} Q[(f_0^2-f^2)^2+(f f_0/Q)^2]}}$, where $\delta I^{r,t}/I^{r,t}$ describes the intensity fluctuations; $\mu(z,\mathrm{F})$ is a function of the component's displacement z and optical frequency F; f_0 the natural frequency of oscillation; T the temperature; m_{eff} the structure's effective mass; and Q its quality factor.

We experimentally study reflectance S^r and transmittance S^t modulation due to thermal motion in both plasmonic and dielectric nanomechanical photonic metamaterials. As an example, Fig. 1b shows the reflectance spectrum for a plasmonic metamaterial (shown inset): sharp peaks correspond to thermal motion of individual nanowires with amplitude, in this case, of ~160 pm. Corresponding reflectivity fluctuations are of order 0.1%, and reach a maximum of 1.5% for an illumination wavelength at the centre of the metamaterial's near-infrared plasmonic resonance. Similarly, for dielectric metamaterials, we observe thermal displacement amplitudes of order 50 pm, which lead to near-infrared transmission fluctuations of order 0.05%.

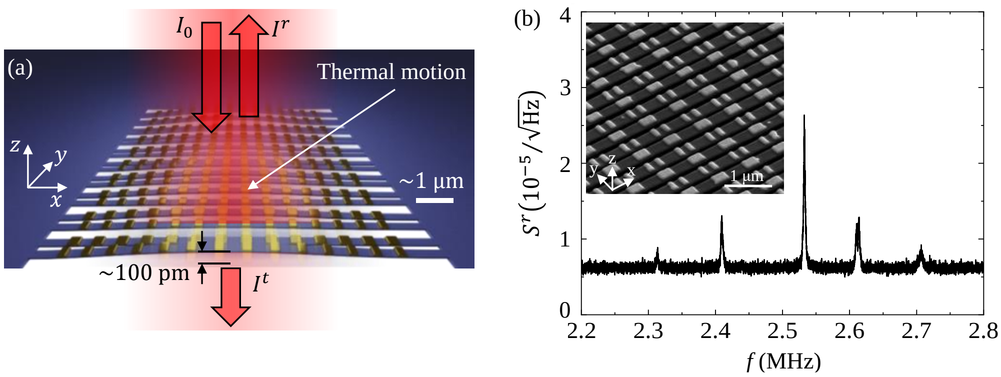

Fig. 1 Fluctuations of optical properties of nanomechanical metamaterials due to thermal motion. (a) An array of mechanical resonators supporting a periodic array of subwavelength optical resonators. Picometric thermal vibrations of individual structural beams modulate the optical properties of the array. (b) Spectral density of reflectance modulation, at a wavelength of 1310 nm, for the plasmonic metamaterial shown in the inset scanning electron microscope image.

These measurements also provide for analysis of variations among the mechanical resonance properties of individual, nominally (by design) identical, nanowires within metamaterial arrays. Differences are found to arise from disparities in nanowire tensile stress of order 30 MPa.

In summary, we demonstrate 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.