Reconfiguring Photonic Metamaterials with the Pressure of Light

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Abstract: Resonant ponderomotive non-thermal optical forces can control the optical response of a nanowire metamaterial. Strong optical nonlinearity achieved via coupling of optical and mechanical resonances enables all-optical transmission modulation at microwatt power levels.

Nanomechanical metamaterials represent a highly adaptable platform of the engineering of profound electro-, magneto- and acousto-optic switching coefficients, and a range of optical phenomena that are vanishingly small, rare or non-existent in natural media. Here, we demonstrate that non-thermal ponderomotive forces generated within opto-mechanical metamaterials, designed to couple near-infrared optical and MHz-frequency flexural resonances, can be engaged to dynamically reconfigure the structure, and thereby to change its optical properties. The mechanical nonlinearity provides for all-optical (light-by-light) modulation of telecoms-wavelength transmission, in a structure $<^{1}/_{3}$ of a wavelength thick, at low ($\mu W/\mu m^2$) intensities. The nonlinearity is, moreover, strongly directionally asymmetric – i.e. dependent upon the direction of light propagation through the metamaterial.

We consider an all-dielectric metamaterial array comprising pairs of dissimilar (long/short) silicon nano-bricks on a free-standing array of flexible silicon nitride nanowires (Fig. 1). Optical forces generated by an incident pump beam induce differential out-of-plane displacements between neighboring nanowires, giving rise to a change in transmission for a CW probe beam. This all-optical light-by-light modulation is seen against the backdrop of optically-induced thermal tuning of the nanowire's natural flexural mode resonance frequencies (Fig. 2), via the dependence of tensile stress in silicon nitride on temperature (i.e. on average incident laser power). These are revealed in frequency spectra of probe transmission as small-amplitude fluctuations derived from nano/picometric 'Brownian' motion of the nanowires (the faint diagonal bands across Fig. 2a); Pump-induced ponderomotive forces drive larger structural displacements and thereby changes in transmission (the sharp spikes in the spectra of

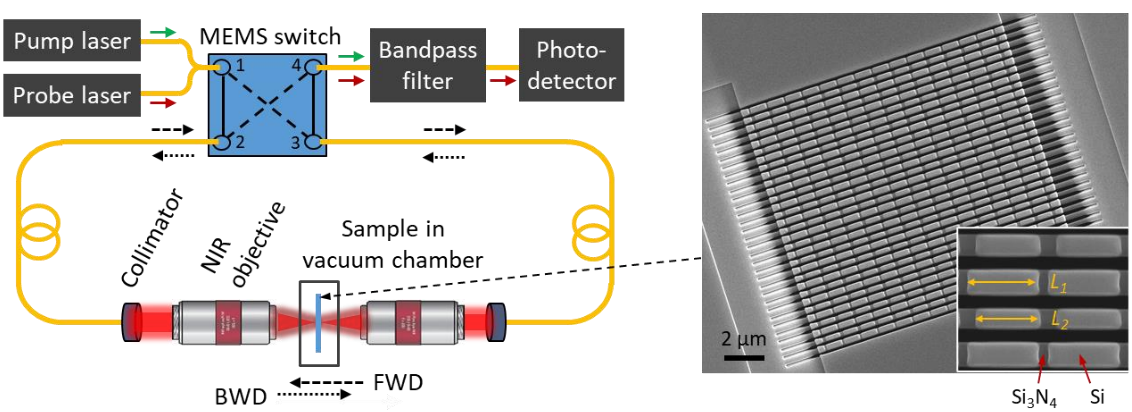

Fig. 1. Simplified schematic of apparatus for pump-probe measurement of metamaterial optomechanical nonlinearity, including a fiber-optic MEMS switch to flip the illumination direction samples. The scanning electron microscope image shows the metamaterial sample, with an inset enlarged section showing the silicon nano-brick on silicon nitride nanowire structure ($L_{1,2}$ = 780, 720 nm).

Fig. 2 at the 6.385 MHz pump modulation frequency), which can reach >30% when that frequency coincides with the nanowires' natural oscillation frequency (at power levels of 12 and 44 μW in the example shown).

Under opposing (forward/backward) directions of illumination, the material and geometric asymmetry of the metamaterial changes the balance among thermal (absorption) and non-thermal (optical force) effects, giving rise to substantive directional asymmetry in its optical response.

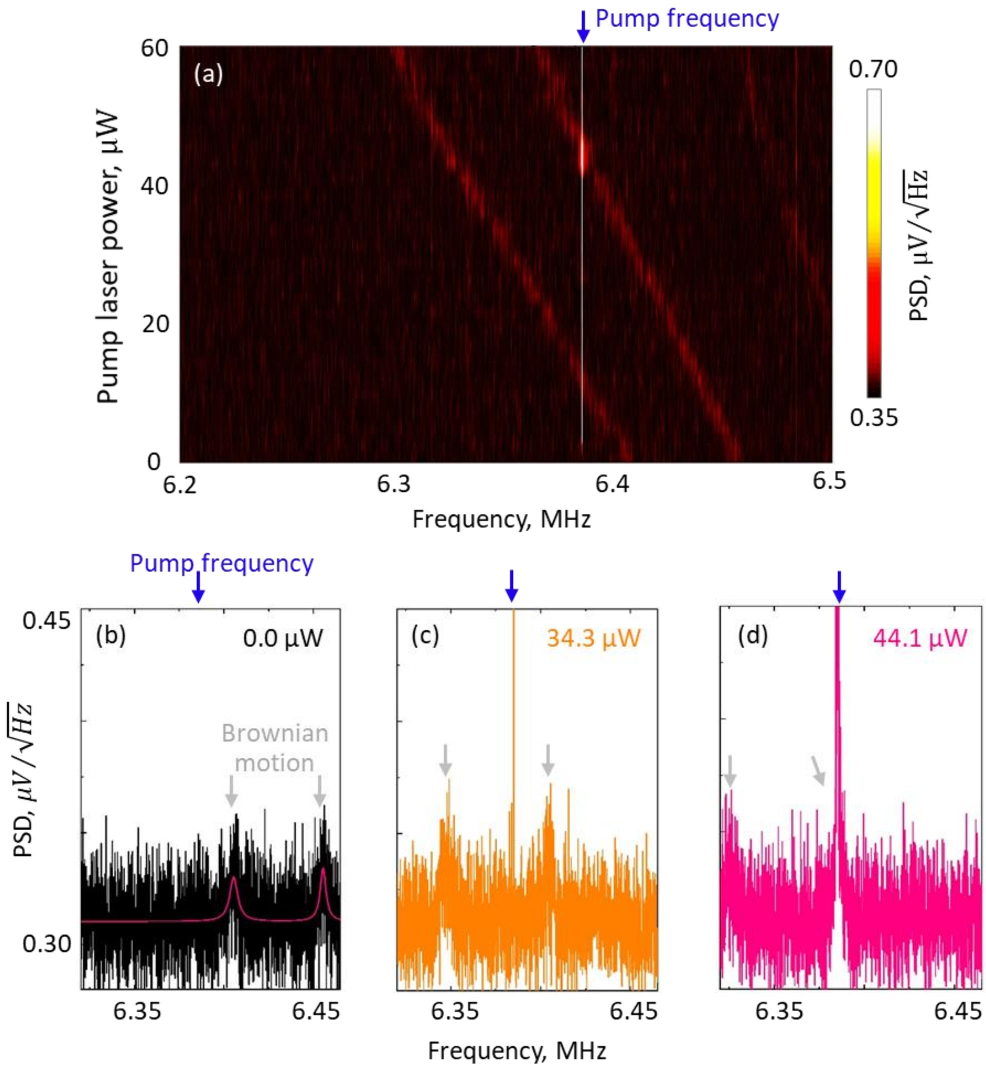

Fig. 2. Power spectral density [PSD] of probe transmission as a function of pump power, with a fixed pump modulation frequency of 6.385 MHz. (b) Transmission PSD at zero pump power [i.e. a horizontal along the bottom edge of panel (a)]. The two small peaks seen in this spectrum, from a sample illuminated only with CW probe light, are associated with the Brownian motion of two individual nanowires at their fundamental out-of-plane flexural mode Eigenfrequencies [which differ slightly by virtue of their different geometries – supporting long/short Si nano-bricks – and thereby effective masses]. (c, d) Transmission PSD at selected pump power levels, as labelled. The Brownian motion Eigenfrequencies red-shift with increasing pump power in consequence of photothermal heating. Non-thermal optical forces drive large amplitude coherent nanowire oscillation at the pump modulation frequency, which is further resonantly amplified when a nanowire's natural oscillation frequency is 'tuned' to coincide with the pump frequency, as in (d).