Reconfiguring metamaterials with the pressure of light

Jinxiang Li[1], Kevin F. MacDonald[1], and Nikolay I. Zheludev[1, 2]

1. Optoelectronics Research Centre, University of Southampton, SO17 1BJ, UK

2. Centre for Disruptive Photonic Technologies & The Photonics Institute, School of Physical and Mathematical Sciences, Nanyang Technological University Singapore, 637371, Singapore

Abstract: The optical response of a nanowire metamaterial can be controlled by resonant ponderomotive non-thermal optical forces. The coupling of optical and mechanical resonances facilitates a strong optical nonlinearity enabling 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 (μW/μm^2) intensities. The nonlinearity is, moreover, strongly directionally asymmetric – i.e. dependent upon the direction of light propagation through the metamaterial.

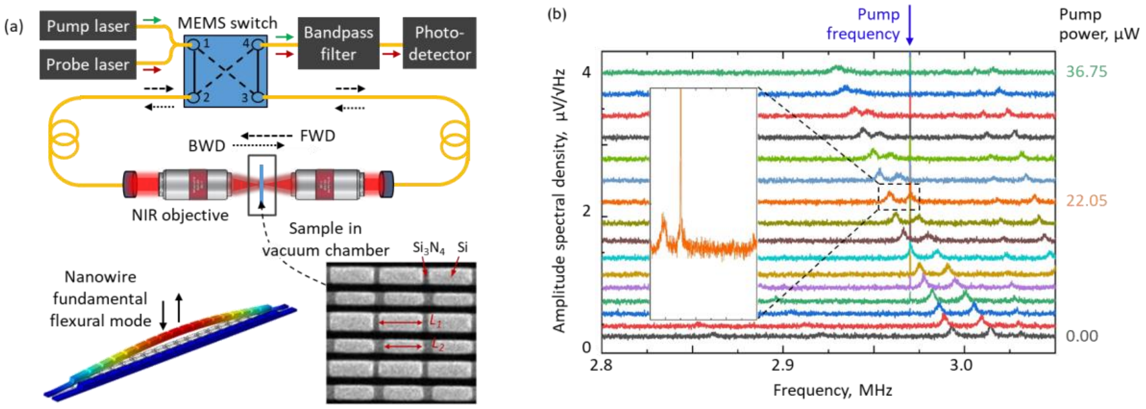

Fig. 1 (a) Simplified schematic of apparatus for pump-probe measurement of metamaterial optomechanical nonlinearity, including a fibre-optic MEMS switch to flip the illumination direction samples. The inset SEM image shows a small section of the silicon nano-brick on silicon nitride nanowire metamaterial [$L_{1,2}$ = 780, 720 nm]. (b) Amplitude spectral density of probe transmission for a range of pump peak power levels, with a fixed pump modulation frequency of 2.97 MHz.

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. 1a). Optical forces generated by an incident pump beam induce differential out-of-plane displacements between neighbouring 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. 1b), 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; Pump-induced ponderomotive forces drive larger structural displacements and thereby changes in transmission, which can reach >30% when the pump modulation frequency coincides with the nanowires' natural oscillation frequency.

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.