Asymmetric Transmission in Nano-opto-mechanical Metamaterials at µW Power Levels

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The reciprocity of optical transmission is a fundamental tenet of linear optics: a medium must transmit light of a given wavelength and polarization identically in the forward and backward directions (unless it is statically magnetized or causes polarization / mode conversion). This symmetry can be broken in nonlinear media and we show here that the opto-mechanical nonlinearity of an all-dielectric metamaterial may yield transmission asymmetry reaching ~60% in a structure $<{}^{1}/_{3}$ of a wavelength thick at low (µW/µm^2) intensities.

Nanomechanical metamaterials have been engineered to exhibit profound electro-, magneto- and acousto-optic switching coefficients, and a variety of optical phenomena that are vanishingly small, rare or non-existent in natural media. Here, we demonstrate that the optical forces generated within free-standing nanomechanical metamaterials can be engaged to dynamically reconfigure the structure in a way that depends upon light propagation direction, enabling the manifestation of strongly nonlinear and directionally asymmetric transmission (Fig. 1a).

We consider an all-dielectric metamaterial array of pairs of dissimilar (long/short) silicon nano-bricks on a free-standing array of flexible silicon nitride nanowires. Under opposing (forward/backward) directions of illumination, optical forces induce different out-of-plane mutual displacements between neighboring nanowires, giving rise to different levels of transmission. In the static regime, numerical modelling indicates that a forward-backward near-IR (telecoms C-band) transmission difference of up to ~60% can be achieved at incident intensities of order 200 µW/µm^2. Experimentally, substantive levels of asymmetry are observed at much lower illumination intensities in dynamic measurements of both thermal (Brownian) and optical pulse-driven oscillatory motion at the structure's few-MHz mechanical resonance frequency.

Transmission is measured using a continuous low intensity probe beam either in isolation (detection of Brownian motion) or in tandem with a coincident modulated pump beam. In frequency spectra of the transmitted probe signal we observe peaks identifiable as those of the bending modes of different nanowires, i.e. those decorated with long/short Si nano-bricks (Fig. 2b). These spectra reveal complex patterns of coupled oscillations underpinned by a combination of, pump/probe power and wavelength dependent, light-induced heating and optical forces. Most importantly, for any set of illumination conditions, marked asymmetries are observed between equivalent peaks in the spectra for opposing directions of illumination: in the example shown, a difference of up to 7% in forward-backward transmission change is observed at pump (peak) intensity of 3 µW/µm^2.

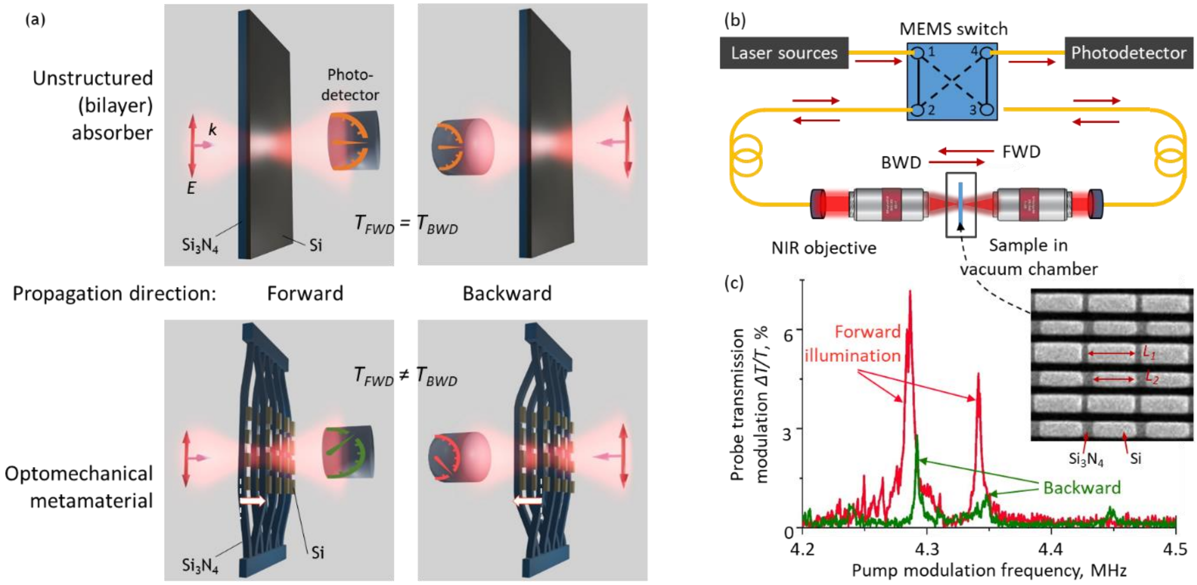

Fig 1 (a) Opto-mechanical transmission asymmetry: [upper row] The transmission of linear media, e.g. an unstructured bilayer of silicon and silicon nitride, must be identical in opposing 'forward' and 'backward' directions of light propagation. [Lower row] The opto-mechanical nonlinearity of a nanostructured bilayer can break this symmetry: the structure is mechanically reconfigured, under the influence of optical forces, differently for the two directions of propagation. (b) Simplified schematic of measurement apparatus, based around a MEMS switch to flip the illumination direction of metamaterial samples, as shown in the SEM image [an array of alternately long/short Si nano-bricks on flexible Si_3N_4 nanowires]. (c) Amplitude of pump-induced change in probe transmission [λ_{probe} = 1540 nm] as a function of pump modulation frequency [λ_{pump} = 1550 nm] for opposing forward [red] and backward [green] directions of illumination.