Transmission Asymmetry in Nano-opto-mechanical Metamaterials

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Abstract: In linear optics, the transmission of (conventional) absorbers is identical in the forward and backward propagation directions. We have developed a nonlinear metamaterial providing intensity-dependent transmission asymmetry of up to 60% at microwatt power levels.

The reciprocity of optical transmission is a fundamental tenet of linear optics: unless a medium is statically magnetized or causes polarization or mode conversion it must transmit light, of a given wavelength and polarization state, identically in the forward and backward directions (Fig. 1a, b). 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 less than one third of a wavelength thick at low (μW/μm^2) intensities.

Nanomechanical metamaterials can be engineered to exhibit profound electro-, magneto- and acousto-optic switching coefficients; to present large effective optical nonlinearities; and to enable the exploration/exploitation of optical phenomena that are extremely small, rare or non-existent in bulk optical media. Here, we demonstrate that the optical forces generated within free-standing nanomechanical metamaterials can be comparable in magnitude to the elastic restoring forces resulting from nanoscale deformation, and as such that they can be utilized to dynamically

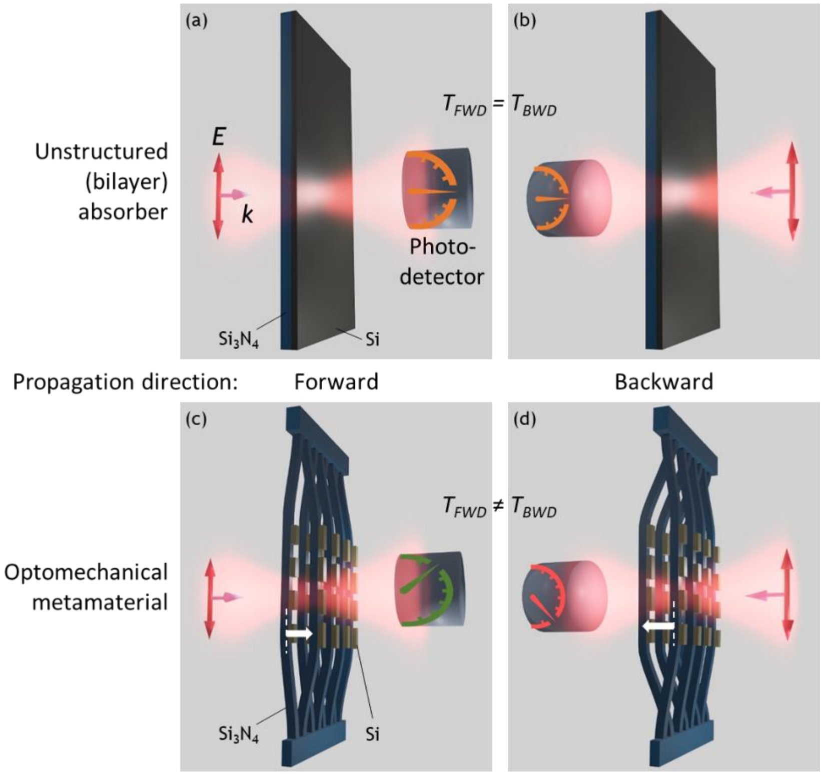

Fig. 1. Opto-mechanical transmission asymmetry. (a, b) Reciprocity requires that the transmission of linear media, such as the unstructured bilayer of silicon and silicon nitride illustrated here, must be identical in opposing - (a) forward and (b) backward - directions of light propagation. (c, d) The 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.

reconfigure the constituent cells in a manner that depends upon the direction of light propagation (Fig. 1c, d). In consequence, the structure can manifest strongly nonlinear and directionally asymmetric transmission, determined by the combination of its optical (near-infrared) and mechanical resonances.

We consider an all-dielectric metamaterial comprised of alternately long (580 nm) and short (500 nm) silicon nano-bricks (115 nm thick) on a free-standing array of (200 nm thick) silicon nitride nanowires. The resonant optical response of the metamaterial is predominantly a function of the high refractive index Si nano-brick structure, i.e. dimensions and relative positions the two bricks (one long, one short) in each unit cell; The (low-index) silicon nitride serves simultaneously as a flexible substrate – allowing for relative displacement of neighboring Si bricks, and to form a directionally asymmetric bilayer – i.e. of optically dissimilar (high/low-index) media. Under opposing (forward/backward) directions of illumination, optical forces induce different directions and magnitudes of differential out-of-plane displacement between neighboring nanowires, giving rise to different levels of transmission. In the static regime, under CW illumination, numerical modelling indicates that an a forward-backward near-IR (telecoms C-band) transmission difference of up to ~60% can be achieved at incident intensities of order 200 $\mu W/\mu m^2$. A substantive level of asymmetry can though be observed at much lower illumination intensities nearly two orders of magnitude lower in a dynamic pulsed excitation regime, by driving the structure optically to oscillate at its few-MHz mechanical resonance frequency.

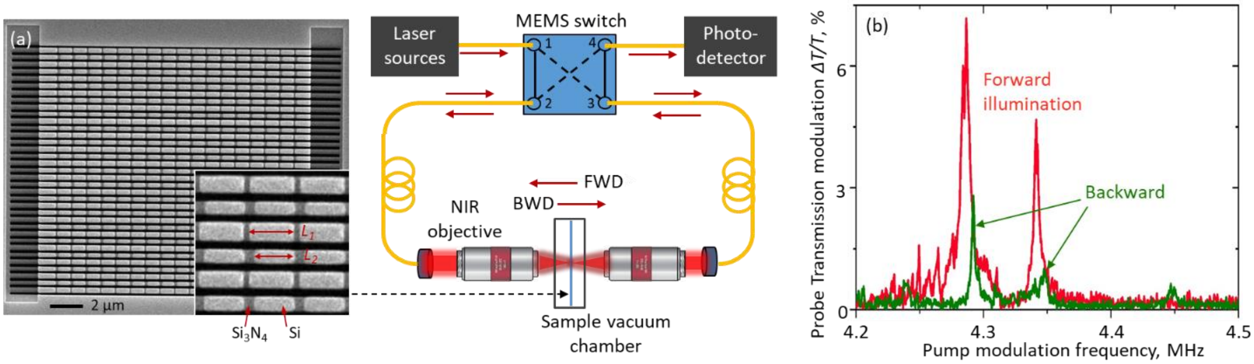

Fig. 2. Experimental measurement of optomechanical metamaterial transmission asymmetry. (a) Simplified schematic of measurement apparatus, based around a MEMS switch to flip between forward and backward illumination directions of metamaterial samples as shown in the SEM image [left, comprising arrays of alternately long/short Si nano-bricks on flexible Si_3N_4 nanowires]. (b) 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.

Experimental samples (Fig. 2a) are fabricated on free-standing 200 nm thick Si_3N_4 membranes coated by chemical vapor deposition with a 100 nm layer of amorphous Si. The bilayer is structured by focused ion beam milling to define the array of asymmetric nano-bricks in the Si layer and parallel supporting nanowires in the Si_3N_4 layer. Optical characterization is performed in a CW-pump/pulsed-probe regime, with the sample under low vacuum (to reduce air damping of nanoscale movement), using and identical arrangement of optical components on either side of the sample and a MEMS switch to flip the direction of light propagation through the sample without moving or adjusting either the sample or any other component in the in/output beam paths (Fig. 2a). Pump and probe laser wavelengths can be tuned against one another and against the metamaterial's optical resonance.

Transmission is measured using a continuous probe beam while sweeping the modulation frequency of a coincident pump beam across a range encompassing the natural mechanical resonances of the nanostructure. (Different pump and probe wavelengths are selected to facilitate isolation of transmitted probe signal using a tunable bandpass filter; An electro-optic modulator controls the pump frequency and provides reference for phase-locked detection of probe signal.) In frequency spectra of the transmitted probe signal we observe peaks at closely-spaced frequencies identifiable as those of the bending modes of different nanowires (i.e. those decorated with long/short Si nano-bricks), as illustrated in Fig. 2b. These spectra reveal complex patterns of coupled oscillations underpinned by a combination of, pump and probe power and wavelength dependent, light-induced heating and optical forces. Most significantly, for any given set of illumination conditions, marked differences (i.e. asymmetries) are observed between corresponding 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 $\mu W/\mu m^2$.