Intrinsic optical bistability in nanomechanical metamaterials at milliwatt power levels

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Abstract: We report the first demonstration of optical bistability in nanomechanical metamaterials - arrays of plasmonic or dielectric resonators on flexible nano-membranes. Bistability results from the nonlinearity of the near-field forces induced by light.

Optical bistability has received considerable attention over many years as it represents a fundamental building block for applications in optical switching, all-optical signal processing, and optical memory devices. The ability to control mechanical motion with optical forces has made it possible to cool mechanical resonators to their quantum ground states, and the same techniques can be used to amplify motion in such systems towards highly nonlinear regimes. Now, nanomechanical metamaterials offer an opportunity to achieve precise control of metamaterial optical properties via light-induced mechanical deformation of nanoscale structures.

An optical power-dependent refractive index change and positive feedback apparatus can together provide a mechanism for optical bistability. It has been predicted that appropriately designed nanomechanical metamaterials can provide both of these components [1]. In such systems, optical pumping excites electromagnetic forces that are comparable to if not stronger than elastic restoring forces, and above a certain intensity threshold the system may be driven into a highly nonlinear regime where two mechanically stable states exist: For a metamaterial comprising an array of asymmetric silicon nanowire pairs, Fig. 1a presents the numerically simulated magnitude of the relative optical force on a pair of neighbouring wires (at fixed illumination intensity), and the corresponding elastic force, as a function of their mutual in-plane displacement. Here, equilibrium points 1 and 3 represent mechanically stable states, while point 2 is unstable (any perturbation will drive the system to either 1 or 3). In consequence, the mutual displacement of the nanowires, and thereby the optical properties of the metamaterial ensemble, is expected to be a hysteretic function of incident light intensity.

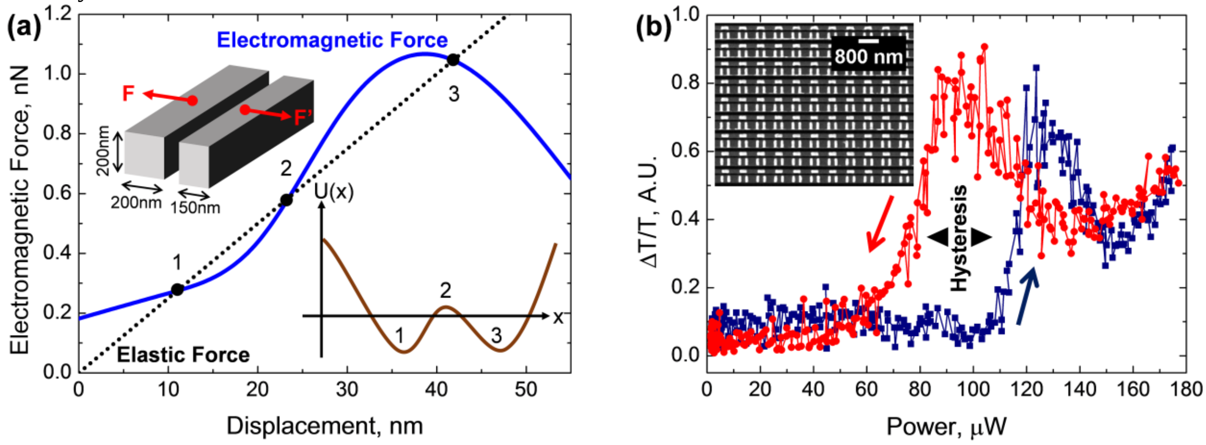

Fig. 1 Bistable nanomechanical metamaterial (a) Computationally simulated balance between optical and elastic forces acting on an all-dielectric (silicon) nanowire metamaterial, as a function of mutual (in-plane) displacement for a fixed illumination intensity. The inset schematically illustrates the net potential experienced by each pair of nanowires vs. displacement. (b) Relative change in probe (1310 nm) transmission for the plasmonic nanomechanical metamaterial shown in the inset scanning electron microscope image, as function of pump (1550 nm) power – blue and red traces denoting increasing and decreasing directions of change in pump power respectively.

We experimentally demonstrate this concept using a NIR-resonant plasmonic nanomechanical metamaterial consisting of Π-shaped plasmonic resonators fabricated by focused ion beam milling in 50 nm thick gold on an array of 50 nm thick silicon nitride nanowires defined in a free-standing membrane (see inset to Fig. 1b). We monitor the optical transmission of the structure at 1310 nm, while pumping with a modulated beam at 1550 nm – a wavelength at which strong differential optical forces are expected. The pump-induced change in probe transmission presents a bistable, hysteretic dependence on pump power, as illustrated in Fig. 1b.

[1] J. Zhang, K. F. MacDonald, and N. I. Zheludev, "Nonlinear Dielectric Optomechanical Metamaterials," Light Sci. Appl. **2**, e96 (2013).