Nanomechanical Bistability in Photonic Metamaterial

Dimitrios Papas[1], Jun-Yu Ou[1], Eric Plum[1], Nikolay I. Zheludev[1,2]

1. *Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, Southampton, SO17 1BJ, UK*
2. *Centre for Disruptive Photonic Technologies, SPMS, TPI, Nanyang Technological University, Singapore, 637371, Singapore*

In mechanical systems nonlinearity is much easier to achieve than in optical systems, e.g. a gravitational pendulum or a string are highly nonlinear devices. This can be used to attain a memory function, where the memory states are based on bistable optical properties of a mechanically-driven nano-opto-mechanical metamaterial.

Here we show that vibrations of an array of nanowires decorated with plasmonic resonators exhibit hysteresis resulting in bistability of the metamaterial's optical properties when the structure is driven by an ultrasonic piezo actuator across its mechanical resonance (Fig. 1). Reflectivity contrast between the bistable states exceeds one order of magnitude and requires only sub-microwatt ultrasonic driving power.

The bistable structure is a free-standing nanomechanical metamaterial supported by a silicon frame that is attached to a piezoelectric transducer. Application of AC voltage to the piezo element generates ultrasound vibrations that result in modulation of the nanomechanical metamaterial's optical properties. When the structure is driven in the nonlinear regime of a mechanical resonance, its response can become dependent on its history of previous excitation, resulting in a hysteresis loop for increasing and decreasing vibration frequencies that originates from different oscillation amplitudes of the nanomechanical structure at the same mechanical frequency Ω (Fig. 1a). We detect the two mechanical states optically, through the optical properties of the resonant plasmonic metamaterial. Transmission and reflection of the metamaterial are studied in vacuum with a focused 70 µW CW laser beam of frequency ω=230 THz (1310 nm wavelength) that is polarized parallel to the nanowires (Fig. 1b). The nanomechanical metamaterial was fabricated by focused ion beam milling on a 100 µm x 100 µm membrane consisting of 50 nm of gold on 50 nm of silicon nitride.

Fig. 1c shows the modulation depth of the metamaterial's reflectivity when mechanically driven at frequency Ω. With increasing driving voltage, the resonance shifts to higher frequencies, while its asymmetry and amplitude increase. The reflectivity modulation becomes dependent on whether the excitation frequency Ω is swept up (black) or down (red). At 0.6 V_{p-p} a maximum optical modulation depth of 22% (1.8%) is recorded at 1.624 MHz as the vibration frequency is increased (decreased), corresponding to 12x optical contrast. About 100 mW power is dissipated by the piezoelectric transducer, however, as the membrane-metamaterial system is about 3.5 x 10^7 times lighter than the transducer and supporting frame, we estimate that sub-microwatt mechanical power drives the bistable response of the membrane-metamaterial system. Indeed, our measurement suggest that 1 nW mechanical power delivered to the membrane may be sufficient to drive the bistable response.

In summary, we demonstrate bistable optical properties due to mechanical bistability of a nano-opto-mechanical system. This work paves the way towards mechanically nonlinear, optically resonant structures that could serve as low-power binary memory elements in photonic systems.

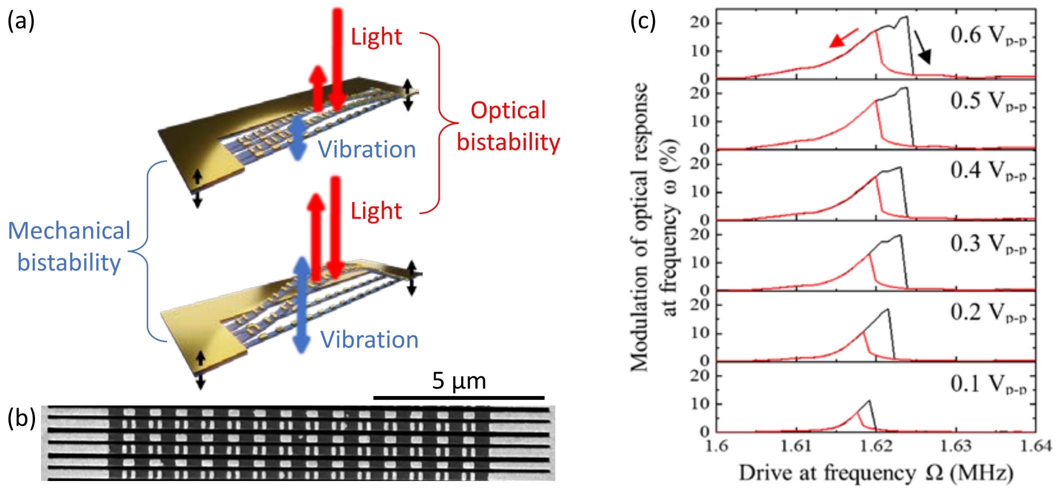

Fig. 1 Optomechanical bistability. (a) Bistable mechanical states of a metamaterial nanostructure cause bistability of its optical properties. Mechanically resonant vibration yields two stable amplitudes of oscillation for the same ultrasound acoustic driving signal at frequency Ω (MHz). The mechanical oscillation controls the coupling between the plasmonic resonators that make up the metamaterial and therefore the mechanical bistability is translated into bistable optical properties at frequencies ω (100s THz). (b) SEM image of a fragment of the bistable membrane-based nanomechanical metamaterial. (c) Evolution of the optically detected mechanical resonance ($\Omega \approx$1.62 MHz) for different driving voltages applied to the piezoelectric element. The resonant optical properties measured with increasing (black) and decreasing (red) driving frequency Ω are different. The structure is bistable, exhibiting different stable optical responses at the same frequency – memory states – that are selected based on the structure's history of excitation.