Optical Bistability of a Nanowire at Microwatt Power Levels

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Abstract: Optically bistable light scattering is observed on oscillating nanowires decorated with plasmonic patterns. Coupling between plasmonic and highly nonlinear mechanical subsystems of the nanostructure facilitates bistability at only a few μW of incident optical power.

The hysteresis of optical properties of nonlinear materials that is observed while increasing and decreasing light intensity is called optical bistability. This is a valuable phenomenon for applications in all-optical data processing, memory, signal routing and displays. However, bistability is difficult to achieve in the optical part of the spectrum as electronic nonlinearities of conventional media are inherently small. A bistable optical response is easier to see in materials undergoing structural phase changes such as chalcogenide films or gallium nanoparticles.

Here, we report for the first time that a profound bistability in light scattering properties can be achieved in a pair of anchored nanowires engaged in highly nonlinear oscillations controlled by incident light – a form of reversible structural change. We argue that metamaterials consisting of arrays of such nanowires shall exhibit bistability in their transmissivity and reflectivity.

The optically bistable device consists of a couple of silicon nitride nanowires operating as nonlinear oscillators of the mechanical sub-system and an array of gold plasmonic meta-molecules on the nanowires representing the optical subsystem of the device, Fig. 1. The restoring force acting on the nanowire enters the regime of high nonlinearity necessary for observation of bistability for out-of-plane displacements comparable to the thickness of the nanowire. The plasmonic resonance of the Π-shaped meta-molecules of coupled gold bars supported by neighbouring nanowires is highly dispersive and sensitive to the mutual positions of the nanowires in the pair. Therefore, bistable oscillations of metamaterial nanowires are transduced into bistability of their optical properties. The device is interrogated at the optical telecom wavelength of 1310 nm (ω = 230 THz) when actuated periodically by a piezoelectric transducer in vacuum at frequencies close to the fundamental natural mechanical resonance of the out-of-plane oscillation of the nanowires, ~ 2 MHz.

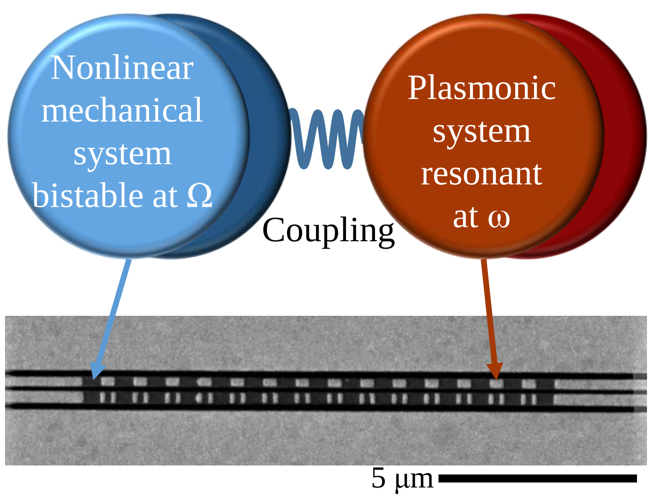

Fig. 1. Optical bistability of oscillating plasmonic nanowires. In the bistable device the highly nonlinear mechanical sub-system of a pair of nanowires is coupled with the array of plasmonic resonators decorating them (SEM image at the bottom). Bistable oscillation of the nanowires can be controlled either acoustically or optically and results in bistable modulation of light.

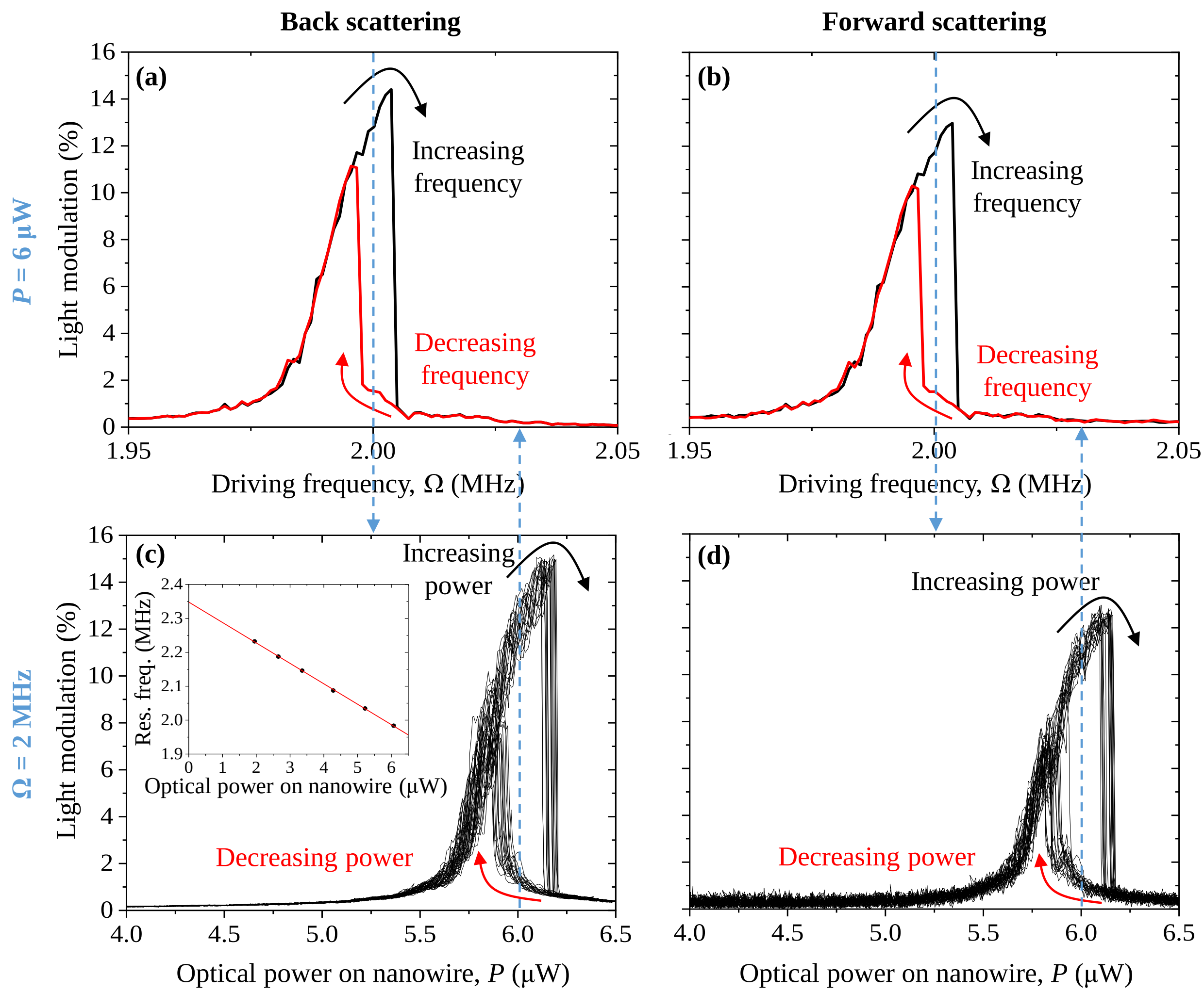

Fig. 2. Demonstration of acoustic and optical control of optical bistability. The amplitude of modulation of the (a,c) backscattered light and (b,d) forward scattered light shows hysteresis upon (a,b) bi-directional sweeping of the driving frequency of the mechanical actuator at a fixed laser power incident on the nanowire of 6 μW, (c,d) laser power bi-directional sweeping at a fixed driving frequency of 2 MHz. The inset of panel (c) shows the dependence of the mechanical resonance frequency on the incident optical power.

When driven to the nonlinear regime, the intensity of light backscattered from the device becomes dependent on its history of previous excitation, resulting in the formation of a hysteresis loop in the scattering intensity. This bistability can be observed by either cycling the frequency of the acoustic actuation (Fig. 2a,b), or by cycling the power of the interrogating light beam (Fig. 2c,d). Optical control of the bistability is caused by a power-dependent shift of the mechanical resonance frequency (Fig. 2c inset). Bistable states with about 15x optical contrast are observed for both forward scattering and backward scattering. Both the optical contrast between the bistable states and the optical power required to engage the bistability can be controlled through the acoustic driving amplitude and frequency (Fig. 2c inset).

We argue that similar bistable responses can be observed in transmissivity and reflectivity of metamaterials consisting of nanowire arrays, for memory/switching applications in low-power photonic circuits.