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Nanomechanically Reconfigurable All-dielectric Metasurfaces for Sub-GHz Optical Modulation

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***Abstract* – Ultra-thin, free-standing, all-dielectric subwavelength-gratings and arrays of nano-cantilevers can act as resonant nanomechanically reconfigurable metasurfaces at telecommunication wavelengths. Actuation by electrostatic and optical forces delivers reversible reflectivity changes up to 20% and a giant sub-GHz frequency optomechanical nonlinearity.**

I. INTRODUCTION

We report on the first experimental demonstrations of free-standing, subwavelength-thickness, all-dielectric nano-grating and nano-cantilever metasurfaces actuated respectively by electrostatic (Fig. 1) and optical (Fig. 2) forces. These devices are manufactured in CMOS-compatible media (silicon and indium tin oxide) and provide, in the first case, reflectivity changes of up to 20% at applied biases of only a few volts, and in the second a substantial optomechanical nonlinearity at intensities of only a few µW per unit cell and a modulation frequency of 152 MHz.

II. METHODS, RESULTS & DISCUSSION

As a means of circumventing the losses and costs associated with the use of noble metals in plasmonic architectures, non-metallic metamaterial nanostructures have drawn considerable attention recently. Various

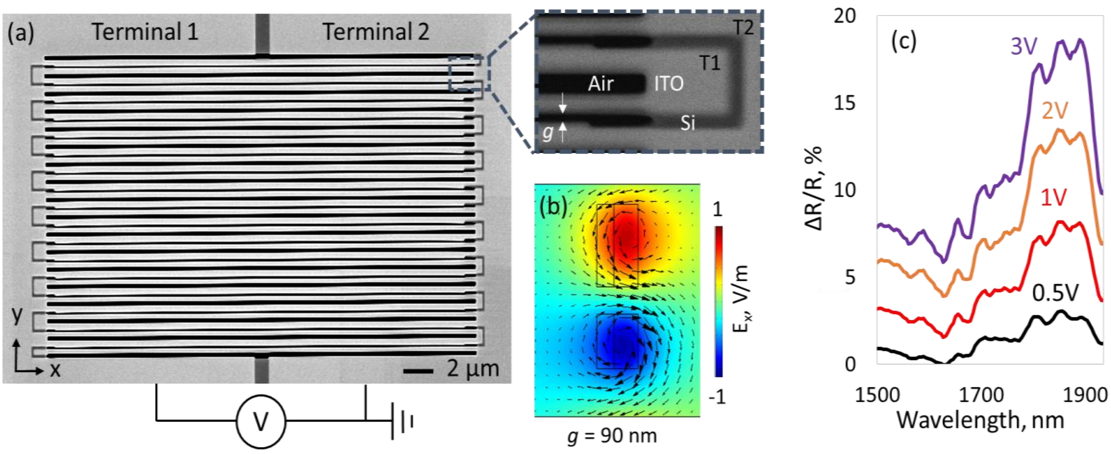

Fig. 1: Electrostatically reconfigurable Si/ITO nano-grating Metasurface: (a) Scanning electron microscope image of a subwavelength grating metasurface in a free-standing silicon/ITO bilayer membrane. Pairs of beams within the array are alternately connected to electrical terminals 1 and 2 [and mutually electrically isolated as illustrated in the inset higher-magnification image]. (b) Computationally simulated map of electric field in the *yz* plane over a unit cell of the nano-grating [a pair of beams] at a wavelength of 1820 nm, for beam separations g = 90 nm. (c) Experimentally measured spectral dependence of relative nano-grating reflectivity change for a selection of applied bias levels [as labelled].

oxides and nitrides [1], graphene [2], topological insulators [3], and high-index dielectrics [4-10] have all been demonstrated, or at least proposed, as potential platforms for the realization of high-Q resonant metamaterials. At the same time, the concept of reversible structural reconfiguration as a paradigm for dynamically switching and tuning the optical response of plasmonic metasurfaces – in response for example to changes in temperature, applied current or electrical bias, magnetic field, or indeed light intensity (taking advantage of the balance among elastic, Coulomb, Lorentz, Ampère and optical forces at the nanoscale) - has become well-established [11].

In the present experimental studies, we harness electrostatic and optical forces to spatially reconfigure the constituent elements, and thereby manipulate the resonant reflection and transmission characteristics, of all-dielectric metamaterials fabricated in free-standing silicon and silicon/ITO bilayer nano-membranes.

Subwavelength grating metasurfaces (Fig. 1) are fabricated in a bilayer membrane of polycrystalline silicon (100 nm thick) and indium tin oxide (ITO, 70 nm) by focused ion beam milling through both layers. The ITO layer alone is further patterned such that alternate asymmetric pairs of Si/ITO beams (c.f. nano-wires) may be subjected to alternately positive and negative electrical bias.

Under said bias, attractive/repulsive electrostatic forces between neighboring beams modify the in-plane spacing *g* between beams (*g* = 100 nm at zero bias). In consequence the optical properties of the metasurface array are substantially changed over a spectral band set by the dimensions of the beams: For light polarized parallel to the nano-grating lines, the structure shown in Fig. 1a presents a 20% change in near-infrared reflectivity under an applied bias of 3V (Fig. 1b). This resonant response is based upon the excitation of antiparallel displacement currents in each pair of silicon/ITO beams, as illustrated by the numerically simulated map of electric field distribution in Fig. 1b (from finite element modelling in COMSOL Multiphysics).

Optomechanically actuated nano-cantilever array metasurfaces are manufactured, again by focused ion beam milling, in 100 nm thick free-standing polycrystalline silicon membranes (Fig. 2a). Geometrically, the structure resembles an asymmetric split ring resonator array as commonly employed in plasmonic metasurface design, but the resonant modes are very different in the high-index dielectric platform. The structure is engineered such that incident light at a pump wavelength of 1550 nm generates optical forces (via the excitation of a predominantly electric dipolar resonance) that tilt the cantilever arms out of the sample plane, bringing about a change in the transmission of the array at a probe wavelength of 1310 nm (by spectrally shifting the magnetic resonance excited in that waveband).

Under continuous illumination the equilibrium displacement of the cantilevers is negligibly small (~a few pm at the cantilever tip) but they can be driven to oscillate at much higher amplitude if the pump beam is modulated

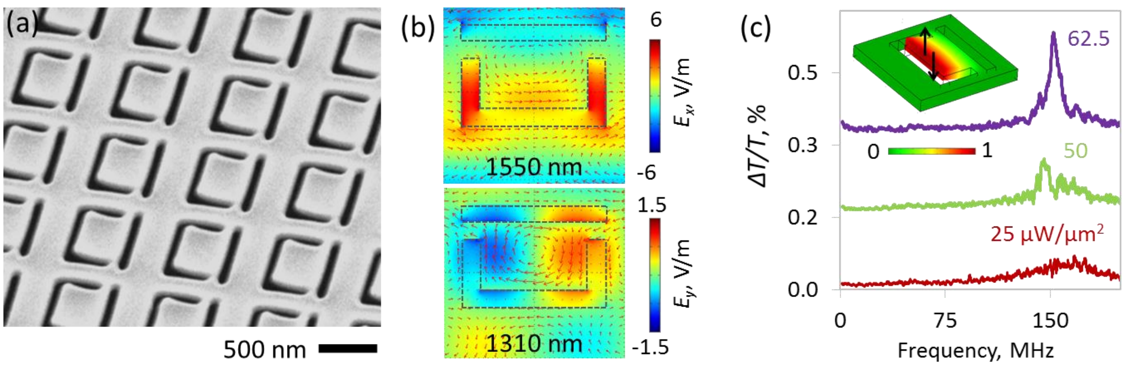

Fig. 2: Optomechanically actuated free-standing silicon nano-cantilever array: (a) Scanning electron microscope image of a section of a silicon membrane nano-cantilever metasurface array [dark areas being slots cut through the membrane]. (b) Computationally simulated map of electric field in the *xy* plane at the mid-point of the membrane thickness for the experimental pump [1550 nm] and probe [1310 nm] wavelengths. (c) 1310 nm probe transmission modulation depth as a function of 1550 nm pump modulation frequency for a selection of peak pump intensities [as labelled]. The inset shows a nano-cantilever unit cell colored according to the relative magnitude of out-of-plane displacement, from numerical modelling, for the structure's first mechanical eigenmode.

at a mechanical eigenfrequency of the structure - the response being enhanced by the mechanical quality factor of the structure, in the present case by a factor of ~100 (Fig. 2c). Under these conditions the metasurface delivers an extremely large optomechanical nonlinearity [12] - an effective susceptibility $Im\{\chi^{(3)}\}/n^2 \sim 3.9\times10^{-14}$ m^{2}V^{-2}, at μW/μm^2 intensities and at modulation frequency of 152 MHz.

III. Conclusion

Free-standing, all-dielectric reconfigurable photonic metasurfaces offer a compact, energy efficient and fast active optoelectronic device platform, exploiting the unique technological and manufacturing opportunities provided by dielectric/semiconductor membranes to provide nanoscale electro-and optomechanical switching functionalities.

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