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All-Dielectric Nano-Opto-Mechanical Metasurfaces

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***Abstract* – We introduce and for the first time experimentally demonstrate free-standing all-dielectric metasurfaces in a variety of ultra-thin, low-loss media. Such structures provide resonant optical properties at near-infrared wavelengths and offer the possibility of extremely strong and fast optical nonlinearities underpinned by nano-opto-mechanical forces.**

I. INTRODUCTION

The noble metals conventionally employed as the foundation of photonic metamaterials suffer from high inherent energy dissipation due to resistive losses, especially in the near-infrared to visible range, which often severely compromise optical properties and limit potential applications. Considerable effort has thus been devoted recently to circumventing these problems in alternative architectures based on low-loss, high-index dielectrics and semiconductors [1-4]. These are invariably 'positive' structures comprising arrays of discrete nanoparticles/rods/rings on transparent low-index substrates, engineered to present resonant responses based on (often coupled) Mie/cavity modes. Breaking with this convention, here we experimentally demonstrate free-standing all-dielectric photonic metamaterials based on 'negative' slot patterns in continuous nano-membranes of media such as silicon nitride and silicon.

II. METHODS, RESULTS & DISCUSSION

Metamaterial designs, typically comprising square arrays of micron scale unit cell slot features such as the ⊓ and asymmetric split ring shapes illustrated in Figs. 1a and 1b, are fabricated in membranes of deeply sub-wavelength thickness by focused ion beam milling. In transmission spectra for such structures, high-quality resonances are observed at near-infrared wavelengths for normally incident light polarized parallel to the opening of the ⊓-slots (Fig. 2a). 3D finite element numerical simulations (Figs. 2b and 2c) reveal that the resonances relate to interactions among a family of bright and dark modes excited within the dielectric structure. Manufacturing imperfections and inhomogeneities currently limit observed quality factors for the resonances to *Q* ~80, but computational models indicate that in principle values several times higher are possible.

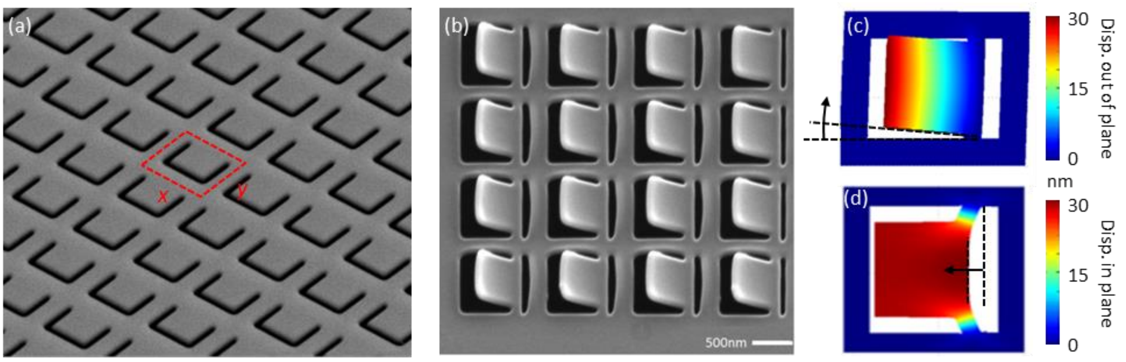

Fig. 1. Scanning electron microscope image [oblique incidence views] of free standing dielectric metamaterials in nano-membranes of (a) silicon nitride [x = 1.2, y = 1.1 µm] and (b) silicon. (c) Computationally modelled out-of-plane and (d) in-plane nano-mechanical displacement modes in asymmetric split ring 'nano-cantilever' metamaterials.

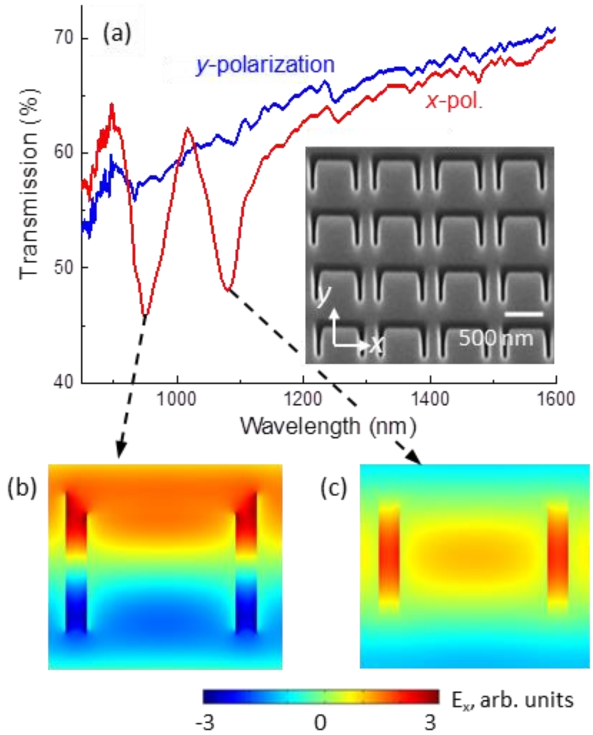

Fig. 2. (a) Experimentally measured transmission spectra, for *x*- and *y*-polarized normally incident light, for the free-standing silicon nitride metasurface shown inset. (b, c) Computationally modelled distributions of the *x* component of electric field in the plane of the membrane at the indicated spectral positions.

Structures of this kind can exploit the unique technological and manufacturing opportunities provided by the dielectric/semiconductor membrane platform, not least their mechanical flexibility: optical forces generated among unit cell elements of low-loss dielectric metamaterials at sub-mW/μm^2 intensities [5] can be engaged to dynamically and reversibly deform elements of the structure (e.g. to deflect a nano-cantilever out-of-plane or to displace it in the plane of the metasurface, as illustrated in Figs. 1c and 1d), providing a mechanism for fast, strongly nonlinear tuning of optical properties at low intensity. Deformations of only a few nanometres are sufficient to dramatically change the optical properties of such structures and will be maximized at their mechanical Eigenfrequencies, which may be in the hundreds of MHz range.

III. CONCLUSIONS

We demonstrate that free-standing all-dielectric metasurfaces present a versatile platform for the realization high-*Q* near-infrared resonant optical properties in ultrathin structures, and open a path to the engineering of giant, high-frequency nonlinear optical responses, driven by resonant opto-mechanical forces.

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