Giant electro-optic effect via electrostriction in a dielectric nano-mechanical metamaterial

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Abstract: Effective electrostriction and electro-optic coefficients orders of magnitude larger than those of bulk dielectrics are achieved in a free-standing metamaterial array of silicon/conductive-oxide nanowires subject to reversible nanoscale deformation induced by an applied electric field.

Electrostriction is a property of all naturally occurring dielectrics whereby they are mechanically deformed under the application of an electric field. Here we demonstrate that an artificial metamaterial nanostructure comprising arrays of dielectric nano-wires, made of silicon and indium tin oxide, is reversibly structurally deformed under the application of an electric field, and that this reconfiguration is accompanied by substantial changes in optical transmission and reflection, thus providing a strong electro-optic effect. Such metamaterials can be used as the functional elements of electro-optic modulators in the visible to near-infrared part of the spectrum: We demonstrate a modulator operating at 1550 nm with effective electrostriction and electro-optic coefficients orders of magnitude larger than those of bulk dielectric media. With a resonant optical response that can be spectrally tuned by design, modulators based on the artificial electrostrictive effect may be used for laser Q-switching and mode-locking among other applications that require modulation at megahertz frequencies.

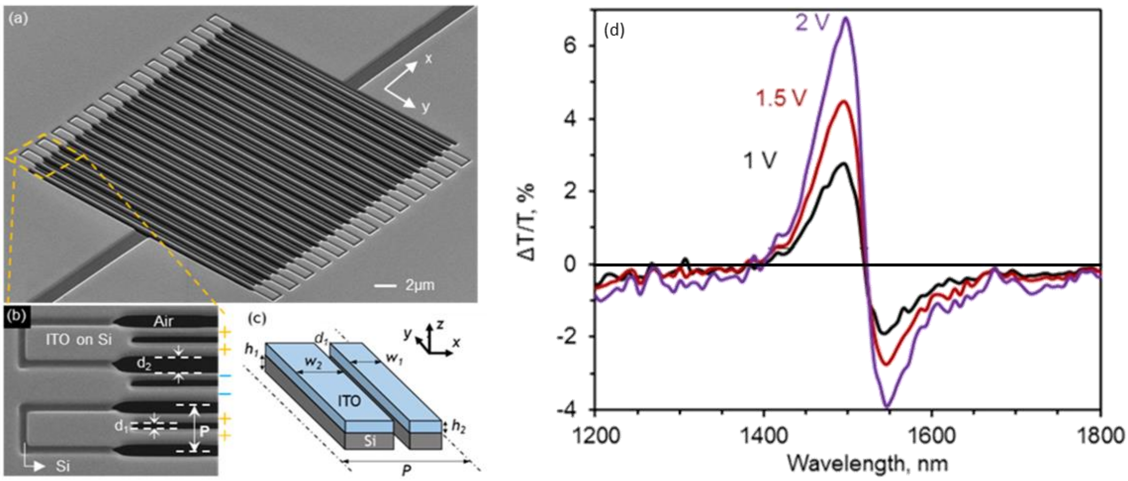

Fig. 1 All-dielectric, nano-mechanical metamaterial EO modulator. (a) Electron microscope image of a nanowire array metamaterial manufactured on a Si/ITO bilayer membrane; (b) Detail of structure at the ends of the nanowires; (c) Geometric schematic of the asymmetric nanowire pair within each period of the metamaterial array. (d) Spectral dispersion of the relative change in transmission of the Si/ITO nanowire metamaterial for a selection of applied static electrical bias levels [as labelled].

Devices comprise an array of nanowires manufactured on a free-standing bilayer membrane of silicon and ITO (Fig. 1a-c), with each period containing an asymmetric pair of closely spaced Si/ITO strips. The optical response of the nanowire array is predominantly determined by the structural geometry of the high-refractive-index silicon component while the ITO layer provides electrical connectivity to facilitate electrostatic tuning of the gap sizes.

In the static regime, transmission changes of up to 7% at a wavelength of 1550 nm are obtained under an applied bias of 2V, giving an effective electro-optic coefficient ($\sim 10^{-6}$ mV^{-1}) approximately five orders of magnitude larger than lithium niobate. Optical modulation amplitude is enhanced, for a given (peak) bias, when the structure is driven at its mechanical resonance frequency – in the present case, 1550 nm transmission changes of up to 3.5% are obtained with a 0.5V control signal at a frequency of ~6.5MHz. The corresponding effective electrostriction coefficient ($\sim 10^{-13}$ m^2V^{-2}), relating the magnitude of unit cell deformation (strain) to applied electric field is three orders of magnitude larger than can be found in bulk dielectrics.