Metamaterial electro-optic switch of nanoscale thickness

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We demonstrate an innovative concept for nanoscale electro-optic switching. It exploits the frequency shift of a narrow-band Fano resonance mode in a plasmonic planar metamaterial induced by a change in the dielectric properties of an adjacent chalcogenide glass layer. An electrically stimulated transition between amorphous and crystalline forms of the glass brings about a 150 nm shift in the near-infrared resonance providing transmission modulation with a contrast ratio of 4:1 in a device of subwavelength thickness. © *2010 American Institute of Physics*.
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Nanophotonic applications, in particular, photonic data processing circuits, require active devices of subwavelength dimensions. However, electro-optic modulation of light in a device of nanoscale thickness is not a trivial problem. In conventional modulators exploiting the Pockels or Kerr effects, the polarization switching involved requires the interference of two propagating modes to develop over distances far in excess of the wavelength of light. The dimensions of such modulators in the propagation direction are often in the centimeter range. Signal modulation via control of the waveguide absorption coefficient or refractive index is another possibility. However, this approach also requires substantial propagation lengths over which an amplitude or phase change accumulates, or it involves interferometric arrangements that are inherently longer than the wavelength of light. It has been suggested that strong signal modulation may be achieved in nanophotonic devices, despite very short propagation lengths, through the use of materials that show a substantial change in absorption or refraction in response to a control excitation: the relative change in the real and/or imaginary parts of the refractive coefficient must be of the order of unity and this can only be achieved in metals, where phase changes can bring about significant changes in optical properties. Such functionality has been extensively demonstrated with elemental gallium, which can exist in phases with radically different optical properties. In this case, phase changes lead to a modification of the plasmon and interband absorption to provide a platform for nanoscale active devices.[1–3]

Here we demonstrate another approach to nanoscale electro-optic modulation that relies not on absorption modulation but rather on a change in the refraction of a material associated with a control-input-induced phase change. In a layer of nanoscale thickness, such a refractive index change would be insufficient to noticeably modulate the intensity or phase of a transmitted wave. However, we demonstrate that by combining a nanoscale layer of phase-change material with a planar plasmonic metamaterial (Fig. 1) one can exploit the fact that the position of narrow resonant absorption lines in certain metamaterials are strongly dependent on the dielectric environment; switching the dielectric layer in contact with such a metamaterial produces a massive change in its resonance frequency. Importantly, given that the planar metamaterial also has a subwavelength thickness, the whole modulating structure can be much thinner the light wavelength. Moreover, the resonance frequency, and therefore the spectral band of high-contrast switching, can be engineered by design and located anywhere within the entire transparency range of the dielectric phase-change medium. The obvious switchable dielectric candidates for the realization of

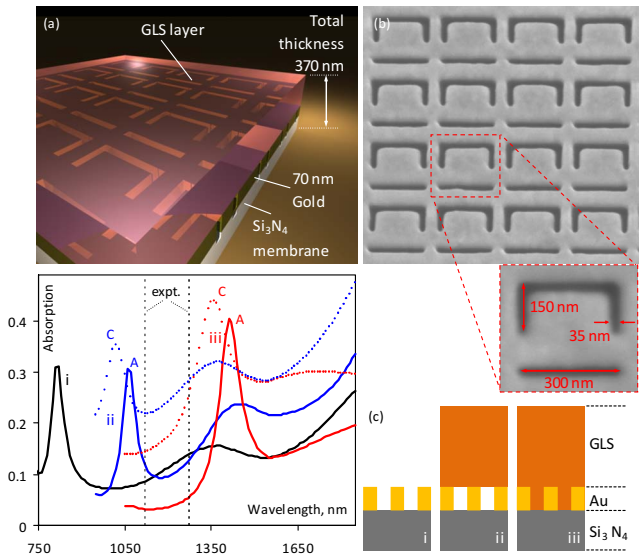

FIG. 1. (Color online) Metamaterial electro-optic switch: (a) artistic impression of the hybrid device structure comprising a planar gold plasmonic metamaterial on a silicon nitride membrane, covered with GLS chalcogenide glass. (b) Electron microscope image of the asymmetric split-ring (ASR) slit array metamaterial before GLS deposition. The inset shows the dimensions of an individual unit cell. (c) Computed optical absorption spectra of the ASR structure (i) without GLS film; (ii) when the GLS forms a flat layer over the metal nanostructure without filling the slits; (iii) when the GLS also fills the slits in the gold [see schematics to the right of the plot]. The solid and dashed lines correspond to amorphous (A) and crystalline (C) phases of GLS, respectively. The vertical dashed lines indicate the experimentally observed positions of the absorption resonance for the two chalcogenide forms.

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this concept are the chalcogenide glasses found at the heart of today's rewritable optical disk technologies[4] and next-generation nonvolatile electronic memories.[5] With threshold switching properties (an ability to be rapidly and reversibly switched between amorphous and crystalline phases with markedly different electromagnetic properties) more robust than alternative phase-change media,[6,7] they have become the materials of choice for such commercial applications. We now show that their functionality can be brought to bear in the metamaterials domain to create switching devices: We demonstrate a high-contrast, near-infrared, electronically addressed optical switch based on a chalcogenide glass hybridized with a nanostructured plasmonic metamaterial.

The selection of an appropriate metamaterial structure is crucially important to such applications. Our experiments employ a planar structure belonging to a class of metamaterials that support trapped-mode plasmonic excitations.[8] In such metamaterials, weak coupling of the excitation mode to free-space radiation modes creates narrow reflection, transmission, and absorption resonances with asymmetric, Fano-type dispersion. The earliest example of such a metamaterial was a periodic array of metallic wire asymmetrically-split ring (ASR) resonators that has found numerous applications where sharp spectral features are required.[6,7,9–11] Here we used a structure complementary to the wire ASR metamaterial: a periodic array of ASR slits in a metal film (see Fig. 1).

The metamaterial structures were fabricated by focused ion beam milling through a 70 nm thick gold film evaporated on a 100 nm thick Si_3N_4 membrane. A gold film surface roughness of 2–3 nm was obtained using low pressure (10^{-8} mbar) thermal evaporation. 30×30 μm^2 metamaterial arrays with a square unit cell size of 375 nm were manufactured on the gold-coated membrane. A 200 nm thick amorphous film of gallium lanthanum sulphide (GLS) was then sputtered under a 3 mTorr argon atmosphere onto the nanostructured metal from a target prepared by melt quenching and annealing a mixture of high-purity gallium sulphide and lanthanum sulphide precursors. GLS is a semiconducting chalcogenide glass with transparency band extending from 500 nm to 11 μm, i.e., covering most of the visible and near infrared spectral range. With a melting temperature of over 900 °C [more than 300° higher than more familiar phase-change materials such as germanium antimony telluride (GST) alloys] it offers exceptional thermal stability. It is also electronically robust; in our own tests, 100 nm GLS films sandwiched between molybdenum electrodes were subjected to more than 10^6 cyclical excitations between 0 and 20 V at a frequency of 3 Hz, and ramped to 100 V with no sign of thermal or electrical breakdown in either case.

Figure 1(c) shows the trapped-mode absorption line of the metamaterial structure and the hybrid metamaterial-GLS device (for amorphous and crystalline forms of GLS) computed using a three-dimensional finite element method to solve Maxwell's equations. This model compares a situation where the GLS completely fills the slits in the metal nanostructure and forms a flat 200 nm layer on top of the gold with one where the slits remain unfilled beneath the 200 nm top layer. These calculations employed experimentally determined values of the dielectric parameters for GLS and data for gold and silicon nitride from Ref. 12. A polarization direction of incident light perpendicular to the ring resonator split was selected to ensure excitation of the trapped-mode

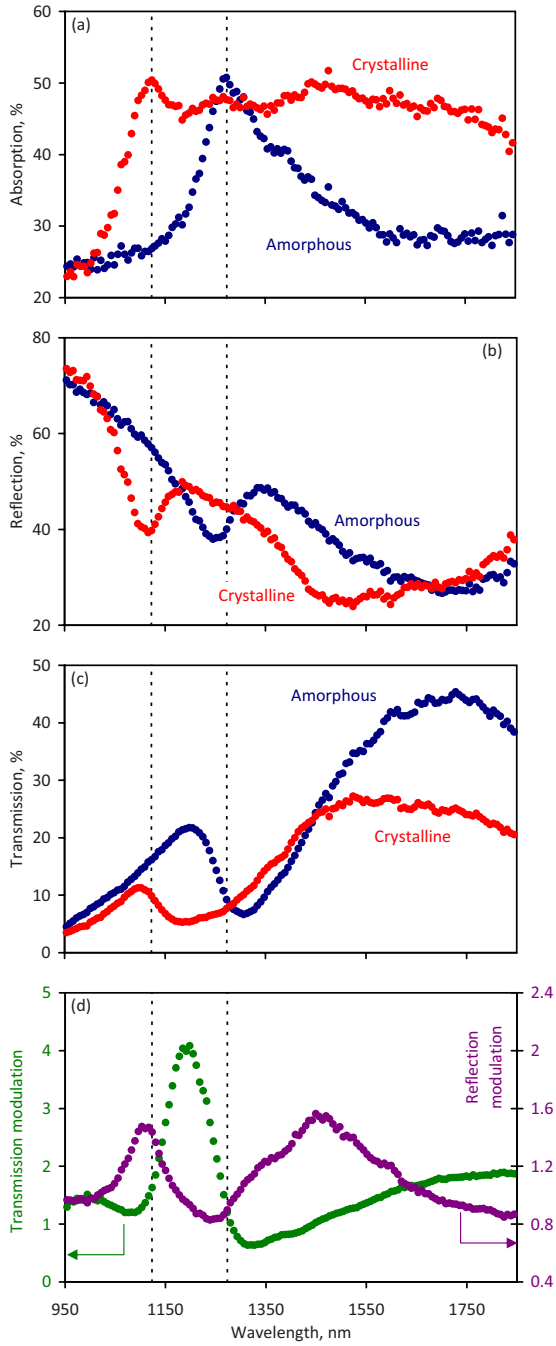

FIG. 2. (Color online) Metamaterial electro-optic modulator switching characteristics: (a) absorption; (b) reflection; and (c) transmission spectra for the amorphous and crystalline phases of the chalcogenide glass layer. (d) Spectral dispersion of transmission and reflection modulation contrast associated with chalcogenide phase switching in the hybrid structure. In all cases the polarization of incident light is perpendicular to the split in the ring resonators to ensure excitation of the trapped-mode resonance. The vertical dashed lines trace absorption resonance positions from panel (a).

plasmon. These calculations are in good qualitative agreement with the experimental data on absorption [Fig. 2(a)]. We observed substantial changes in the metamaterial's optical properties as a result of GLS functionalization. All resonance features exhibit the anticipated redshift resulting from the reduction in plasmon frequency due to the presence of the high refractive index GLS layer. Following hybridization with GLS the metamaterial's absorption spectrum accrues a background associated with the additional absorption of the GLS layer and the broadening of the plasmon peak due to

increased damping. This is more pronounced in the more conductive crystalline phase. A comparison with the experimentally measured positions of the absorption lines indicates that a partial filling of the nanoscale slits in the gold film has been achieved.

The transmission, reflection, and absorption characteristics of the device were quantified at normal incidence using a microspectrophotometer [Figs. 2(a)–2(c)]. Transmission switching was demonstrated by applying 10 ms pulses of incrementally increasing voltage between the patterned gold layer and an electrode brought into contact with the top surface of the GLS.[13] By using a Keithley 238 electrometer for this purpose, the electrical properties of the GLS film could be monitored in real time, providing for facile identification of the transition point: the chalcogenide maintains a high (amorphous-state) resistivity until the applied voltage reaches approximately 45 V, at which point abrupt threshold switching occurs. This transition to the more conductive crystalline state (occurring through localized Joule heating) brings about a dramatic blue-shift of 150 nm in the spectral position of the hybrid metamaterial's trapped-mode resonance. As has been previously reported,[13] the characteristic transition time for amorphous-to-crystalline switching in GLS is of the order 50–100 ns.

As a consequence of this resonance shift, the transmission of the hybrid structure changes by as much as a factor of four within a wavelength band centered at 1198 nm [between the absorption peaks associated with the two forms of GLS—see Fig. 2(d)]. The reflectivity changes resulting from phase switching are also substantial, reaching almost 60% at both 1103 and 1450 nm. Thus, the hybridized metamaterial acts as a transmission switch, providing a contrast ratio of 4:1 in a device structure less than one third of a wavelength thick.

In summary, the phase-change media behind rewritable optical disk technologies and emerging electronic memory devices have been shown, in combination with planar photonic metamaterials, to offer an innovative paradigm for the development of nanophotonic switching devices. A high-contrast electro-optical metamaterial switch has been demonstrated using a bistable, CMOS (complementary metal-oxide semiconductor) and/or SOI (silicon-on-insulator) compatible chalcogenide glass. The demonstrated device (showing unidirectional switching with a 45 V control input) is less than one third of a wavelength thick and may be structurally engineered to operate at wavelengths throughout the visible and infrared spectral range. We expect that the reverse switching transition may be induced at higher potentials, while careful engineering will reduce the required voltage levels for both switching directions, making this technology compatible with real world photonic applications.

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