Chalcogenide Glass Photonics: Non-volatile, Bi-directional, All-optical Switching in Phase-change Metamaterials

B. Gholipour[1], J. Zhang[1], F. Al-Saab[1], K. F. MacDonald[1,*], B. E. Hayden[2], D. W. Hewak[1], and N. I. Zheludev[1]

1. Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, Southampton SO17 1BJ, UK
2. School of Chemistry, University of Southampton, Southampton SO17 1BJ, UK
** kfm@orc.soton.ac.uk*

Abstract: Non-volatile, bi-directional, all-optical switching in a phase-change metamaterial delivers high-contrast transmission and reflection modulation at visible and infrared wavelengths in device structures only $\sim{}^1/_8$ of a wavelength thick.

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We report on the first demonstration of non-volatile all-optical switching in plasmonic metamaterials functionalized with phase-change chalcogenide glass. The switching results in high-contrast modulation of transmission and reflectivity in the visible-to-infrared range and is achieved at optical excitation levels below 0.25 $mW/\mu m^2$ in device structures only $\sim{}^1/_8$ of a wavelength thick (Fig. 1). These hybrid materials provide a robust and versatile platform for a new generation of optical switching and memory devices.

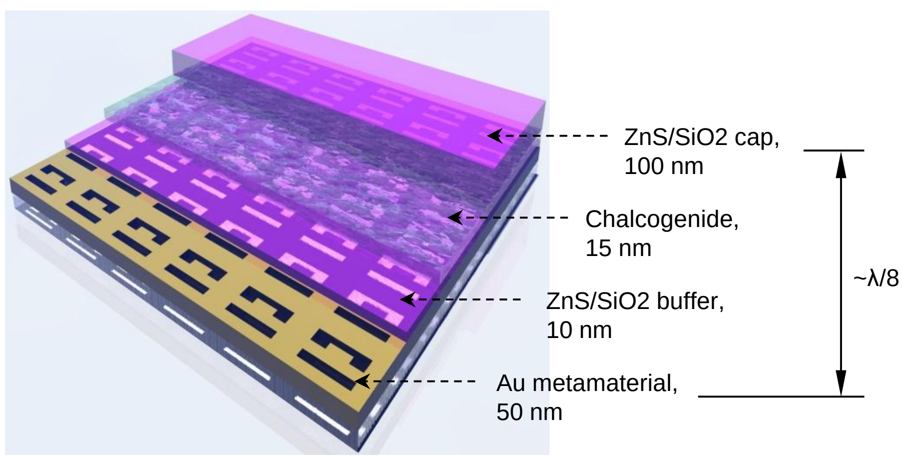

Fig. 1: Layer structure of chalcogenide hybrid metamaterial switch.

Switching optical signals on the nanoscale is not a trivial problem: conventional modulators exploiting the Pockels or Kerr effects are based on interference over distances much longer than the wavelength, necessitating devices with dimensions of several centimeters in the propagation direction. Modulating a signal by controlling the absorption coefficient or refractive index of a medium also requires substantial propagation lengths over which amplitude/phase changes accumulate, or interferometric arrangements that are inherently longer than the wavelength.

Here we demonstrate an approach to nanoscale all-optical modulation based on the fact that the resonant optical properties of a plasmonic metamaterial strongly dependent on the near-field dielectric environment: small changes in the in the refraction of an adjacent chalcogenide nano-layer (associated with optically-induced transitions between its amorphous and crystalline states) produce massive changes in the transmission and reflection characteristics of the hybrid structure. The selection of an appropriate metamaterial pattern is crucially important to such applications. Our experiments employ a planar structure belonging to a class of metamaterials that support trapped-mode plasmonic excitations. 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.

Experimental device structures comprised: a calcium fluoride or fused quartz substrate; a 50 nm thick gold metamaterial film (patterned photolithographically or by focused ion beam milling with a square array of asymmetric split ring resonators); a functional 15-40 nm film of chalcogenide glass ($Ge_2Sb_2Te_5$, GST glass sputtered under argon); and inert ZnS/SiO_2 buffer and capping layers either side of the chalcogenide film (to prevent metal diffusion into the glass and degradation in air at elevated phase transition temperatures).

Phase transitions were initiated uniformly across large (~2000 μm^2) areas of the GST film by single-pulse laser excitation, with pulse energy and duration (down to 50 ns) optimized separately for the forward (amorphous-crystalline) and reverse (crystalline-amorphous) transition directions. This phase switching in the chalcogenide layer of the hybrid metamaterial produces marked changes in its transmission and reflection spectra (measured with a microspectrophotometer). The amorphous-to-crystalline transition in GST increases its refractive index and red-shifts the resonance frequency of the metamaterial, bringing about a substantial change in optical properties at wavelengths in the vicinity of the resonance, as illustrated in Fig. 2.

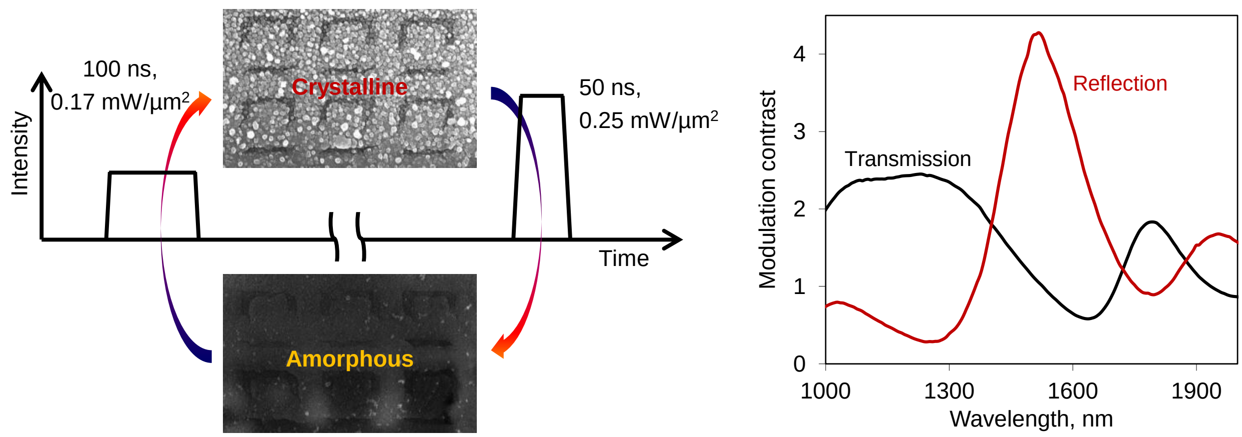

Fig. 2: All-optical near-IR chalcogenide metamaterial switching: Single pulse laser excitations convert the GST layer between amorphous and crystalline states uniformly across the entire metamaterial array (a total area of ~2000 μm^2; inset electron microscope images show much smaller areas encompassing only six 400 nm ASR cells), thereby switching the reflectivity and transmission of the hybrid structure with high contrast at wavelengths close to the metamaterial resonance.

Ternary chalcogenide glasses (GST and others, such as gallium lanthanum sulphide - GLS) present enormous scope for compositional tuning and optimization of electromagnetic and physical properties and ‘high-throughput’ materials discovery techniques provide for efficient exploration of this parameter-space: compositional gradients of material deposited over substrate areas of several square centimeters by physical vapor deposition are rapidly analyzed to reveal optical (e.g. refractive index), thermal (transition temperature) and electrical characteristics that depend strongly on chalcogenide composition and film thickness.

Chalcogenide phase-change metamaterials can be switched electronically and thermally as well as optically to produce high-contrast intensity and phase modulation, and may be engineered through metamaterial design to function at any visible to mid-infrared wavelength within the chalcogenide’s transparency range. As such they offer a versatile platform for the development of a new generation of nanoscale optical switching, memory and spatial light modulation devices.