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Optically Reconfigurable Metadevices Based on Phase-Change Materials

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***Abstract* – Chalcogenide phase-change media provide a uniquely flexible platform for both nanostructured and optically-rewritable all-dielectric metamaterials. Non-volatile, laser-induced phase transitions enable resonance switching in nanostructured chalcogenide meta-surfaces and allow for reversible direct-writing of arbitrary meta-devices in chalcogenide thin films, including dynamically re-focusable, chromatically correctable and super-oscillatory lenses, and near-infrared-resonant photonic metamaterials.**

I. INTRODUCTION

The metamaterial paradigm allows us to control and tailor the optical response of materials to achieve otherwise unattainable properties and unprecedented functionalities in novel ‘metadevices’ [1]. To mitigate the substantial ohmic losses suffered by plasmonic materials, which compromise many applications, research attention has turned recently to all-dielectric metamaterials [2]-[3]. At the same time, reconfigurable metamaterials have attracted considerable interest for their ability to offer adaptive and dynamically controllable optical properties ‘on demand’ [4]-[5]. Phase-change media offer the possibility to realize reconfigurable all-dielectric metamaterials because their phase state can be reversibly switched through thermal cycling in non-volatile fashion, leading to large changes in optical and electrical properties [6]-[8]. Here, we demonstrate dielectric metamaterials formed both via nanostructuring of chalcogenide thin films (Fig. 1a), wherein optically-induced phase changes can be employed to switch the resonant optical response characteristics, and via direct, reversible laser-writing into the phase-change medium (Fig. 1b), paving the way for the engineering of compact reconfigurable optoelectronic metadevices. The latter, unlike existing reconfigurable materials which retain their basic structure during reconfiguration, can be erased and re-written at will to introduce completely different optical structures as required.

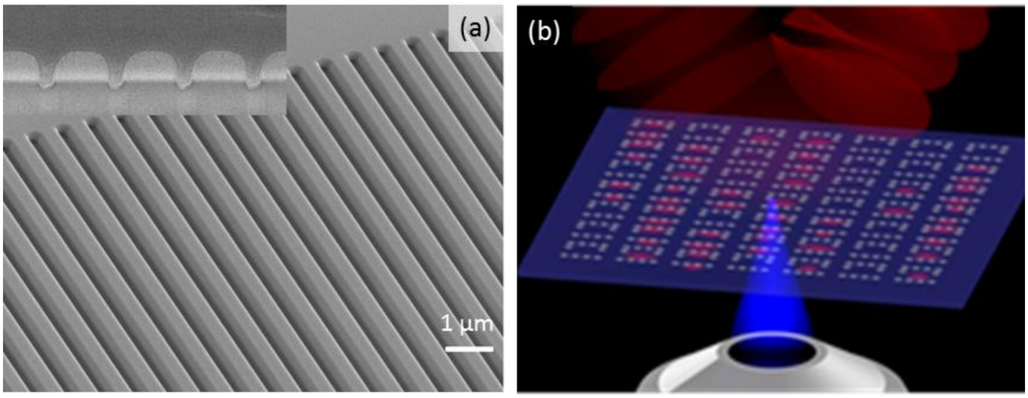

Fig. 1. **Nanostructured and laser-rewritable phase change meta-devices:** (a) Optically switchable nano-grating spectral filter fabricated in thin film GST [oblique incidence scanning electron microscope image and inset cross-sectional image]. (b) Artistic impression of the direct-write system, showing one meta-surface optical element being erased and another being written with sub-micron spatial resolution into a GST film using femtosecond laser pulses.

II. METHODS, RESULTS AND DISCUSSION

Our work employs sputtered nanoscale thin films (30 – 250 nm) of the chalcogenide phase-change medium $Ge_2Sb_2Te_5$ (GST). In the first instance, films are structured by focused ion beam milling with meta-surface, non-diffractive, sub-wavelength grating patterns that present high-quality near-infrared transmission resonances at wavelengths dependent on the nano-grating period (Fig. 2a). The GST film can be converted from its as-deposited amorphous phase to the crystalline state by optically-induced heating, to a temperature above its glass-transition point T_g but below its melting point T_m, using a continuous wave excitation at a wavelength of 532 nm and intensity ~3 mW/μm^2. In consequence, the structure's transmission stop-band is spectrally red-shifted by as much as 150 nm, bringing about high-contrast changes in reflection and transmission in the spectral range around the resonance (Fig. 2b). With appropriate selection of pulsed laser excitation parameters (to momentarily bring the GST to a temperature $>T_m$), phase-change meta-surface spectral filters of this kind may be reversibly and repeatedly switched in the manner of the functional chalcogenide thin film in rewritable optical discs.

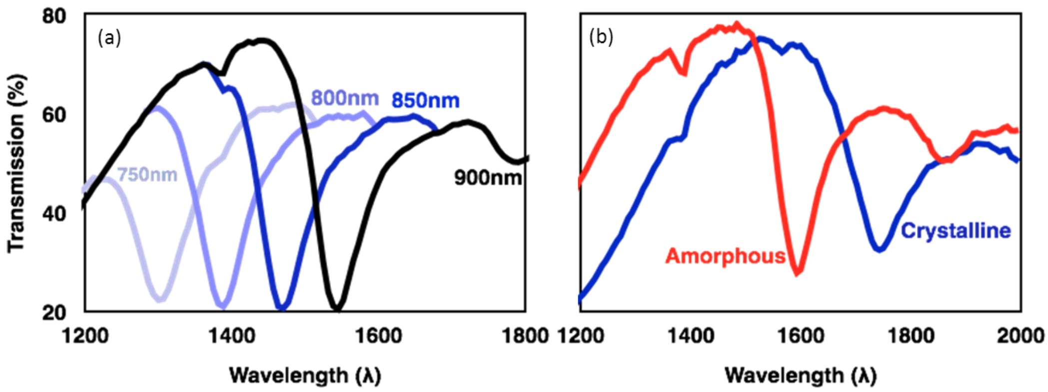

Fig. 2. **GST nano-grating spectral filters:** (a) Transmission spectra for nano-gratings, such as illustrated in Fig. 1a, with a range of structural periods [as labelled] fabricated in as-deposited amorphous phase GST films. (b) Transmission spectra for the amorphous and optically-switched crystalline phases of an 800 nm period GST nano-grating filter.

We also employ GST thin films as a 'canvas' for femtosecond-laser-written meta-surface structures. Patterns are formed sub-micron pixel-by-pixel using trains of low-energy (0.28 nJ) 730 nm femtosecond pulses incident on the GST canvas via a microscope objective lens (Fig. 1b). Individual pulses only deliver sufficient energy to partially convert the chalcogenide from its amorphous to its crystalline state, and thus the size and contrast of any given crystallized mark can be precisely controlled by changing the number of pulses and/or pulse energy applied. Single, high-energy (0.95nJ) femtosecond pulses can be employed to selectively melt and rapidly quench

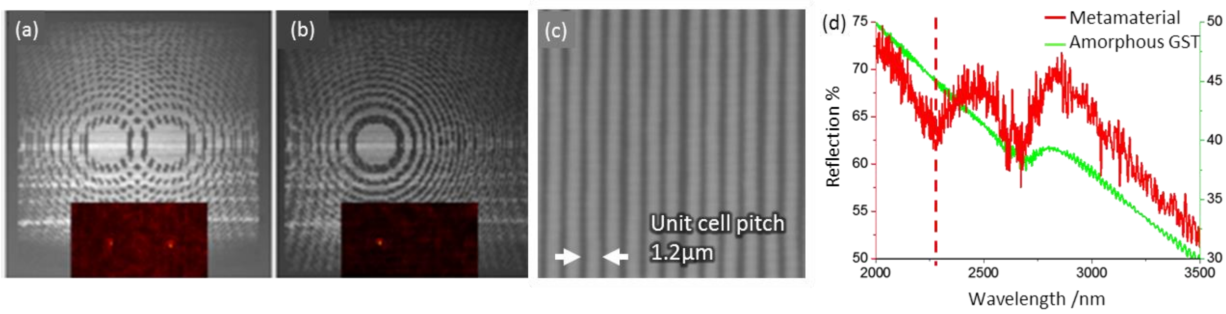

Fig. **3 Laser-re-writable phase-change meta-devices:** (a) Microscope image of a dual Fresnel zone-plate laser-written in a GST thin film, which forms a pair of focal spots [under 730 nm plane wave illumination] as shown inset. (b) Reflection image of the same sample, optically reconfigured as a single Fresnel zone-plate (the other being erased), correspondingly producing a single focal spot as shown inset. (c) Microscope image of non-diffracting metamaterial grating. (d) Reflection spectrum of the metamaterial showing a clear resonance (dotted red line), compared to unstructured GST.

crystalline marks, returning them to the amorphous state. The application of this optical direct-write/erase technique to the production of reconfigurable optical elements is illustrated in Figs. 3a and 3b. Figure 3a shows a dual Fresnel zone-plate pattern with 50 μm focal length written point-by-point into a GST film in binary phase-state contrast (dark grey = fully amorphous; light grey = fully crystalline). A plane wave incident on the zone-plate is focused to a pair of bright focal points as shown inset. The pattern is then reconfigured to remove the right hand zone-plate without altering the left hand one. The resulting pattern and corresponding single focal spot are shown in Fig 3b. We can also use the same technology to write non-diffracting metamaterials for the IR, as shown in Fig 3c. The reflection spectrum of the metamaterial (Fig 3d) shows a clear resonance at 2.2 μm which is not present in the unstructured GST spectrum.

III. Conclusion

We present two approaches to the realization of non-volatile, optically reconfigurable, all-dielectric metadevices using chalcogenide phase-change media: Optically-induced transitions between amorphous and crystalline states in nanostructured chalcogenide thin films provide high-contrast switchable spectral filtering functionality at near-infrared wavelengths selected by design geometry. Direct laser writing into chalcogenide thin films using carefully controlled femtosecond doses of laser energy to incrementally crystallize sub-micron domains of the medium (and to erase crystalline marks) allows for the creation of arbitrary, re-writable planar optical elements and all-dielectric metamaterials.

Acknowledgement

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