Filtering and Modulation from Visible to Terahertz using Phase-Change Extraordinary Optical Transmission Metasurfaces

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ABSTRACT

Periodic arrays of sub-wavelength-scale holes in plasmonic metal films are known to provide resonant transmission/reflectance peaks via the extraordinary optical transmission (EOT) effect. Active control of the spectral position of such transmission/reflection peaks can be obtained by adding a layer of phase-change material (PCM) to the EOT device. Switching the PCM layer between its amorphous and crystalline states shifts the spectral position (and usually the amplitude too) of the resonance, so enabling potential applications in the fields of active filtering and sensing (e.g. for multispectral imaging) and optical modulation. Here we report the design, fabrication and characterization of active EOT devices targeted at various important regions of the optical spectrum

Key words: extraordinary optical transmission, tuneable filter, phase-change metasurface.

1. INTRODUCTION

Extraordinary optical transmission (EOT) devices normally consist of periodic arrays of sub-wavelength holes in a thin plasmonic metal film [1], providing transmission spectra with features mainly determined by the array period and hole size. Figure 1 shows examples of EOT devices designed to operate in the mid-infrared (mid-IR) spectral range (with array periods chosen to deliver transmission peaks at a number of specific mid-IR wavelengths); periods can be made smaller or larger for devices respectively operating from visible wavelengths to the terahertz regime.

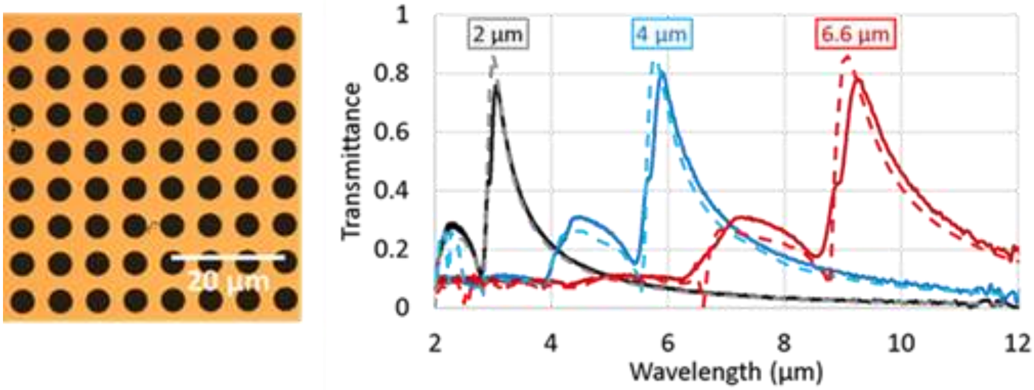

Figure 1. (Left) Microscope image of a 6.6 µm period EOT array in a 100 nm Au film on CaF_2 substrate. (Right) Simulated (dashed lines) and measured (solid lines) spectra having a range of periods (from 2 to 6.6 µm) yielding various peaks in the mid-IR.

Adding a phase-change material (PCM) layer to EOT devices changes the local optical environment and, as a result, the transmission spectrum. The switching of the PCM layer between its fully amorphous and crystalline phases further modifies the spectrum, shifting the transmission peak's central wavelength, reducing the transmission amplitude and decreasing the [2, 3]. This leads to the possibility of both active filtering (in which the device allows light of different wavelengths through) and optical modulation (where the device provides a great contrast in transmission at a particular desired wavelength).

2. EXPERIMENTAL

By way of example, we show here the development of a PCM-EOT metasurface device for operation in the mid-infrared waveband. A 40 nm Au film was deposited onto a CaF_2 substrate via thermal evaporation and patterned with a square array of circular holes via wet-etching to create a

4 µm period EOT film. A 70 nm $Ge_2Sb_2Te_5$ PCM layer and an 8 nm Si_3N_4 capping layer (to prevent oxidation of the PCM) were then deposited on top of the EOT film via sputter deposition. Finite element simulation (using Comsol Multiphysics) of the expected transmission spectra was carried out, and experimental spectra were measured using Fourier transform infrared (FTIR) spectroscopy.

3. RESULTS & DISCUSSION

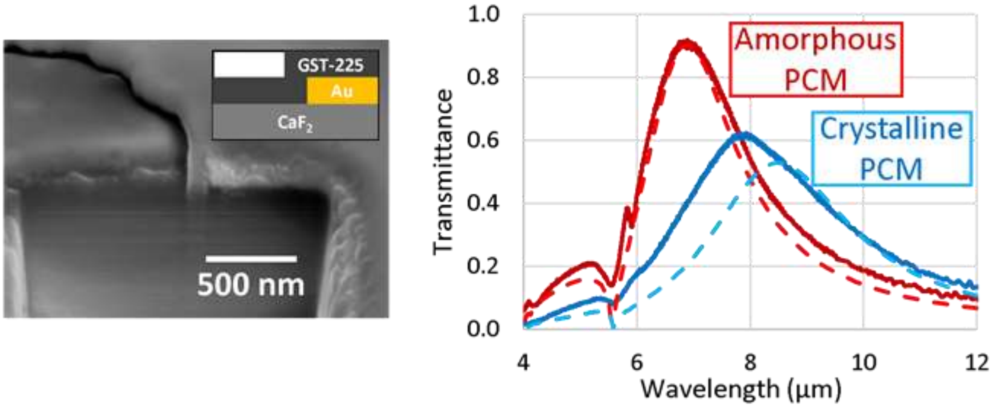

Figure 2. (Left) Cross-sectional SEM image with graphic insert of the active EOT device showing the material layer structure at the edge of an array hole. (Right) Simulated (dashed lines) and measured (solid lines) transmission spectra with the PCM layer in both amorphous (red lines) and crystalline (blue lines) states.

An SEM cross-section of a typical device is shown in Figure 2, along with simulated and experimental transmission spectra (between which we note that there is good agreement). A significant red-shift of the transmission peak is seen upon crystallization of the PCM layer; this is due to the increase in the real part *n* of the refractive index upon crystallization. A broadening of the peak and a reduction in its amplitude is also evident, and this is due to the higher value of the extinction coefficient *k* for the crystalline phase. Although here we show a device designed for MIR operation, PCM compositions are available with a wide variety of optical contrasts (differences in *n* and *k*) across the entire optical range (e.g. Sb_2S_3 and Sb_2Se_3 for the visible range, GeSbSeTe compositions for the near IR range), enabling active EOT devices of the type described to be realized from the visible to the long-wave infrared. In the THz regime we find that the relatively large (cf. other spectral wavelengths) *k* value of the crystalline phase of common PCMs leads to almost complete suppression of the EOT transmission peak upon crystallization of the PCM layer, providing the possibility of novel THz modulators with large contrast ratios based on the EOT effect. We also note that the fabrication of EOT arrays can be readily scaled-up for manufacture using laser processing techniques [4].

4. CONCLUSIONS

We have successfully designed and demonstrated experimentally PCM-based EOT metasurfaces with the potential for application as active optical filters in the mid-infrared. Designs for operation in other wavelength ranges have also been developed. In the THz regime, similar devices can be used to provide fast and efficient modulation.

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