Active Phase-Change Metasurfaces for Convolutional Image Processing

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ABSTRACT

Non-local phase-change optical metasurfaces are designed for reconfigurable free-space edge-detection/bright-field and edge-detection/blurred imaging functionality. Active reconfigurability is achieved via switching the phase-change material between crystalline and amorphous states. Applications include fast pre-processing for image analysis, optical microscopy and more.

Key words: phase-change, metasurface, edge detection, reconfigurable

1. INTRODUCTION

Analog optical computing has gathered increasing attention over recent years due to advantages it possesses over digital electronic computing, including intrinsic parallelism, low-loss transmission and ultra-high bandwidth, for specific use cases [1]. Previously, optical computing systems that are both fast and energy efficient have been demonstrated for implementations such as neural networks [2] and matrix-vector multiplication [3], via the utilization of both free-space and integrated photonic systems. The work presented here uses a free-space configuration to perform edge detection with reconfigurability to switch to either bright-field imaging or image blurring (smoothing) modes. Edge-detection is a simple yet crucial part of image processing and a variety of static edge detection metasurfaces have been presented previously (e.g. [4]). The designs presented here are integrated with chalcogenide phase-change materials (PCMs) to allow dynamic switching between functionalities. PCMs exhibit highly contrasting optical properties (n and k) when switched between their amorphous and crystalline states, which can be achieved using a heat stimulus [5]. Here we demonstrate, via simulation, 2D polarization insensitive edge detection with switching to either bright-field mode imaging or image smoothing using non-local metasurfaces in the infrared spectral regime.

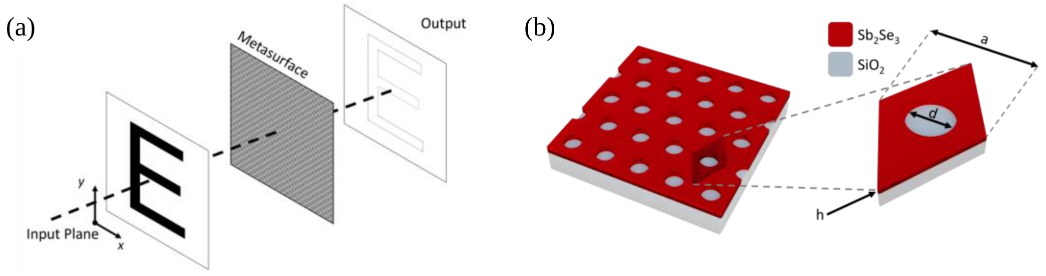

Figure. 1: (a) Schematics of a system that utilizes a non-local PCM metasurface for edge-detection directly in the spatial domain. The PCM metasurfaces can be reconfigured to switch to and from their amorphous and crystalline states, which in turn switches the metasurfaces from an edge-detection mode to a bright-field imaging mode or image blurring mode. (b) Unit cell structure of circular holes on a hexagonal lattice in a thin Sb_2Se_3 layer. The unit cell is defined by the lattice constant a, the diameter of the holes, d, and the thickness of the Sb_2Se_3 layer h.

Figure 1a displays a schematic of a system for edge-detection using a non-local phase-change metasurface. The meta-atoms are identical throughout the metasurface, which aids with ease of fabrication. In optical systems, edge-detection functionality is typically implemented via transfer functions that mimic second-order differentiation [4]. Hence, the desired transfer function is parabolic in transmission amplitude, with the transfer function for bright-field imaging simply being a flat (high) transmission amplitude, and that for image blurring being effectively a low-pass filter. Figure 1b shows the general metasurface design used, which consists of a hexagonal lattice of circular holes in a thin Sb_2Se_3 layer.

2. RESULTS & DISCUSSION

Figure 2a displays the metasurface transmission profile with the Sb_2Se_3 layer in the crystalline state (red lines) for a design having edge-detection functionality (and here working at λ=1540 nm). Edge-detection up to angles of ±30 ° is obtained, with the hexagonal array giving access to relatively polarization insensitive performance in 2D, as previously shown for non-reconfigurable Si metasurfaces [6]. Our design, when switched to its amorphous state (blue line), switches to a bright-field mode functionality. The simulated output, for an input image consisting of the letter "E", is shown for both functionalities in Figure 2b.

Figure 2c shows the transmission profile of a reconfigurable design, using the same basic Sb_2Se_3 lattice structure (but with different values for a, d and h), that now performs image blurring (smoothing) in the crystalline state. In the amorphous state the metasuface exhibits a parabolic like transmission, so reverting to edge-detection mode.

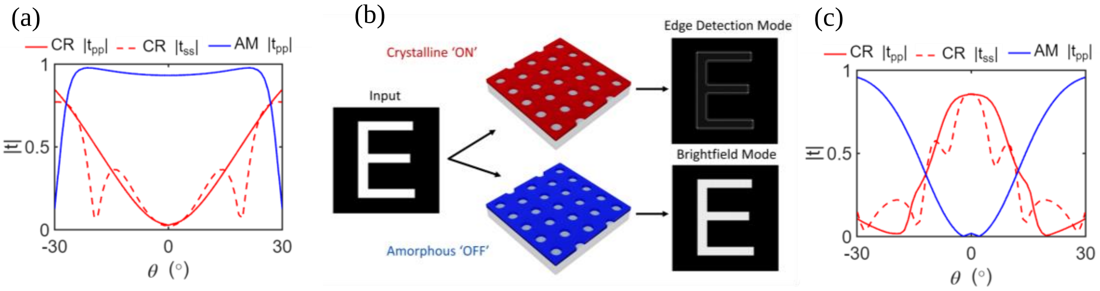

Figure. 2: (a) The transmission amplitude of a 2D polarization insensitive non-local Sb_2Se_3 metasurface, demonstrating a parabolic (edge-detection) response as a function of the elevation and azimuth angle of incident light for the PCM in its crystalline state (red lines). Both s and p polarization responses at an azimuthal angle of 0 ° are shown. In the amorphous state (blue line) a bright-field transmission response is obtained (here, for clarity only p polarization response is shown). (b) The simulated output of this metasurface, for an input image of the letter "E", for both its edge-detection and bright-field imaging modes. (b) The transmission amplitude response of a non-local Sb_2Se_3 metasurface designed to have an image blurring functionality, at a wavelength of λ=1110 nm, in its crystalline state (red lines) for both s and p polarization When switched to its amorphous state (blue line) the device performs edge detection (again, for clarity only p polarization transmission response shown in this case).

3. CONCLUSIONS

In this work, two reconfigurable phase-change optical metasurfaces are presented with the function of edge-detection that can be dynamically reconfigured to, in one case, a bright-field imaging mode and in the other, an image blurring/smoothing mode. In both cases 2D, polarization insensitive operation is achieved.

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