Reconfigurable Metalenses based on Antimony Trisulfide (Sb_2S_3) Phase Change Material

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Abstract: We design and fabricate reconfigurable antimony trisulfide (Sb_2S_3) cylindrical metalenses. Simulation results show focusing efficiencies of 72.85% and 79.7% for focal lengths of 3.5cm and 5cm at a wavelength of 750nm. Experimental verification is underway.

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1. Introduction

Dynamically reconfigurable optics based on phase change materials (PCMs) provide the opportunity for the design of lightweight and space efficient devices. Two-dimensional reconfigurable metalenses made of these PCMs would provide size and weight benefits as compared to traditionally bulky dynamically reconfigurable lenses. PCMs aid in optical modulation when switched from their different volatile or non-volatile phases. The selected PCM for this study is Sb_2S_3, which exhibits a near-IR refractive index contrast of 0.75 at low loss when switched between amorphous and crystalline phases [1,2] (Figure:1C). This switching can be exploited to design Huygens source optical nanoradiators whose careful selection and arrangement can be used to design dynamically reconfigurable metalenses.

2. Metalens Design

2.1 Design principles

The metalens design is comprised of an arrangement of pixelated arrays of homogenous nano-antennas (Figure:1A). The resulting metasurface acts as a wavefront-shaping device; with the wavefront being akin to a cylindrical lens. Individual nano-antenna arrays are optimized to ensure maximum generalized diffraction efficiency in both optical states of the PCM. The optimization parameter utilized is the figure of merit (FOM) first presented in [3]. This design FOM allows for a computationally effective and efficient synthesis of the reconfigurable metalens without the need for a full wave electromagnetic simulation of the entire metalens system in both optical states.

We choose to discretize the continuous (ideal) 0 to 2π phase profile for a 500x500µm^2 cylindrical lens into an arbitrary N = 4 phase levels. To create the discretized wavefronts necessary in both optical states, a total of N^2 = 16 nano-antenna elements are chosen. This selection of elements informs the pixel sizes that are necessary for the wavefront-shaping. To address the coupling issues inherent in low-aspect ratio Huygens metasurfaces [4], an inter-pixel gap of 1.5µm is employed. The effect of this gap on the phase profile of pixels is shown in (Figure:1B); where pixels (1) and (3) are resonant antennas with high E-field confinement within the nano-antenna and pixels (2) and (4) are off resonance with weak E-field confinements. In each case, the effect of the gap and nearest neighbor pixel is negligible for pixel sizes > 10µm.

2.2 Modeling and characterization

The geometry of homogenous arrays of Huygens nanoradiators as low aspect ratio Sb_2S_3 nano-discs in a square lattice arrangement was iterated to create a database of nano-antenna elements in both optical phases. The nano-discs were chosen to enforce two-fold symmetry and therefore polarization independence. Each nano-antenna is encapsulated in a layer of SiO_2 which acts as protective layer for the metasurfaces and prevents the lateral migration of sulfur upon phase changes. The encapsulating layer also acts as an index matching layer with the quartz substrates increasing the efficiency of individual elements. The iterated geometric parameters were limited to the diameter and unit cell spacing while keeping the height fixed at 120nm to account for ease of fabrication. Once the elements with high FOMs are chosen, we calculate the intensity profiles for the designed metalens in each of the optical phases, using Huygens' and field superposition principles. The resultant metalens intensity maps with comparisons to ideal, 4-level discretized and 4-level discretized with inter-pixel gaps are presented in (Figure:1D) and (Figure:1E). Focusing efficiencies, defined as the ratio of intensity within 3 times the FWHM to the total incident intensity [5] is calculated to be 72.85% for the amorphous Sb_2S_3 lens with focal length 3.5 cm, and 79.7% for the crystalline Sb2S3 lens with focal length 5 cm.

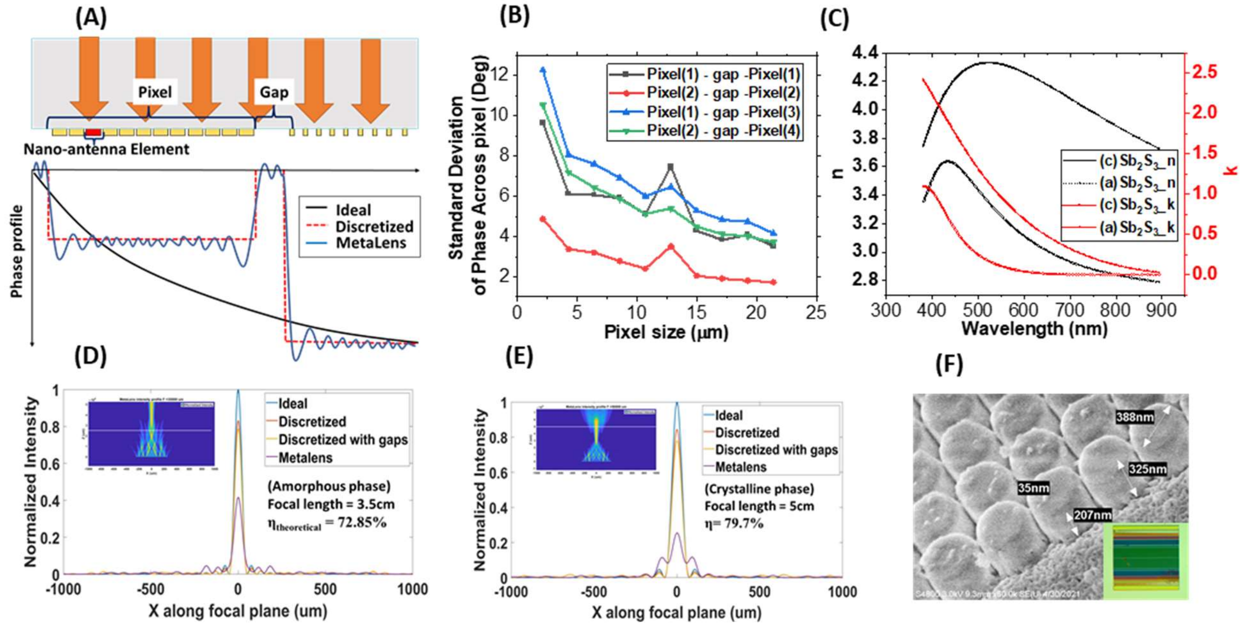

Figure 1: (A) Upper: Metalens elements and geometry definitions and Lower: resultant phase profile for the ideal lens, discretized lens, and metalens; (B) inter-pixel coupling perturbation for Sb_2S_3 nanoantenna arrays (pixel unit cell of 427.5nm; pixel diameters (1) 262.5 nm, (2) 200 nm, (3) 250 nm, (4) 230 nm; (C) Measured crystalline (c-) and amorphous (a-) ellipsometric data for Sb_2S_3 on fused-SiO_2; (D) & (E) Normalized intensity maps at focal plane for (D) amorphous Sb_2S_3 metalens for a design focal length of 3.5 cm, and (E) crystalline Sb_2S_3 metalens for a design focal length of 5 cm; insets show calculated 2-D intensity maps for those metalenses; (F) Fabricated metasurface of amorphous-Sb_2S_3 with SiO_2 capping layer on fused SiO_2 substrate, inset: Optical Microscopy image of partially etched metalens (SiO_2 antennas on Sb_2S_3 on fused-SiO_2)

2.3 Fabrication and Characterization

Sb_2S_3 thin films are created by ion sputtering with in situ substrate heating. Measured refractive index data of the films is comparable to previously reported data [2] (Figure:1C). Raman spectrum of crystalline films also matches previously reported data [2]. The metalenses are fabricated with an SiO_2 capping layer topped with a conductive Carbon layer. The patterns are written using the Raith VOYAGER 100 electron-beam lithography tool and etched off by reactive ion etching. SiO_2 is etched first using a fluorine-based etch recipe followed by resist removal and Sb_2S_3 etch using a chlorine based etch [6]. This stack is then encapsulated with another layer of SiO_2 to form the capping layer. Optimization of nanofabrication, development of optically reversible phase changes, and experimental characterization of these metalens are all in progress.

3. Conclusion

Design and fabrication of an SiO_2 capped Sb_2S_3 based cylindrical reconfigurable metalens has been achieved. Simulated focusing efficiencies of 29.2% and 24.8% at focal lengths of 3.5 cm and 5 cm at 750 nm wavelength have been calculated for a 500x500 μm^2 aperture.

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