Electrically Actuated Zoom-Lens Based on a Liquid-Crystal-Embedded Semiconductor Metasurface

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Primary CNF Tools Used: JEOL 9500, Zeiss Ultra SEM, Oxford Cobra ICP etcher, Oxford PECVD

Abstract:

Planar metamaterials, or metasurfaces, offer an ultrathin and adaptable platform for modulating spatial and spectral properties of light. We engineer semiconductor-based metasurfaces which exhibit tunable optical resonances for photonic applications in near-infrared. We report on the design, fabrication, and characterization of resonant amorphous silicon (a-Si) metasurfaces that act as a voltage-tunable dynamic-focus lenses likely to find uses in augmented reality and other imaging technologies.

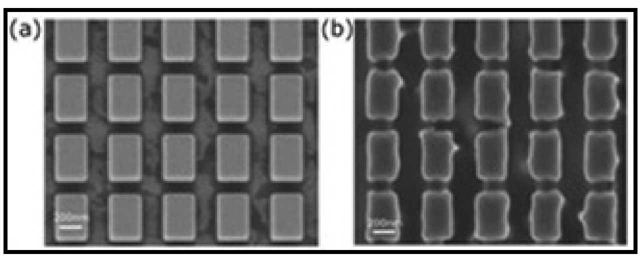

Figure 1: (a) A scanning electron microscope image of a typical a-Si-based resonant metasurface on an ITO-coated SiO_2 substrate. (b) Same as (a), but before improving the fabrication process.

Summary of Research:

Fabrication of a-Si Metasurfaces. Metasurfaces present a compact and scalable alternative to conventional free-space optical elements. Dielectric and semiconductor metasurfaces, such as those consisting of germanium or silicon, can generate near-arbitrary spatial phase profiles with low absorptive losses, leading to high-performance waveplates, beam deflectors, and lenses with subwavelength-thickness [1]. Our project focuses on the design and fabrication of resonant amorphous silicon (a-Si) metasurfaces with sub-100 nm feature sizes and high (up to 1:6) aspect ratios, useful for numerous applications where compact and efficient light modulators are sought. Figure 1a shows a representative a-Si metasurface, consisting of an array of rectangular a-Si prisms patterned on a fused silica substrate. Such regular semiconductor nanoarrays support localized electric and magnetic Mie-type resonant optical modes, which may be spectrally-tuned by modifying the permittivity of the media (e.g., liquid crystals: LC) adjacent to the array. The metasurface fabrication consisted of six steps: plasma-enhanced chemical vapor deposition (Oxford PECVD) of a-Si onto an ITO-coated fused silica substrate and surface treatment with SurPass 3000 adhesion promoter; standard HSQ 6% spin-coat, baking, and e-beam exposure at 6 mC/cm^2 (JEOL 9500FS); development in TMAH/NaCl (0.25/0.7N) salty solution; and pattern transfer to the a-Si layer through an inductively coupled HBr plasma reactive ion etch (Oxford Cobra). The resulting samples were characterized with a scanning electron microscope (Zeiss Ultra). The resulting structures show excellent accuracy in geometric dimensions, a significant improvement over our first-generation metasurfaces produced with MIF300 developer (Figure 1b).

Tunable-Focus Lens Based on a Liquid-Crystal-Embedded a-Si Metasurface. In one application, we apply a-Si metasurfaces towards the design of metalenses with tunable focal lengths. Compact lenses with adjustable focal lengths are essential to modern imaging technologies such as adaptive vision devices and wearable augmented reality displays; however, most metalenses exhibit static functionalities post-fabrication. Our work uses a-Si metasurfaces infiltrated with liquid crystals (LCs) to demonstrate a varifocal metalens with voltage-actuated focal length [2]. This is accomplished through the design of a resonant a-Si metasurface encapsulated in a LC cell. The latter behaves as an anisotropic dielectric medium with

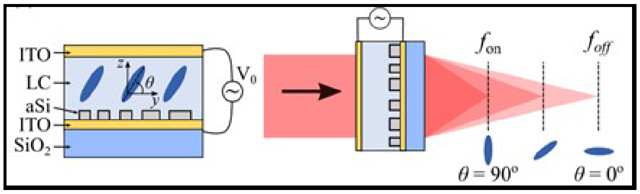

Figure 2: Schematic of the device. Left: A silicon-based metalens is encapsulated in a liquid crystal cell between two transparent conducting oxide electrodes. An AC voltage is applied to the electrodes, driving the orientation of the LC molecules at angle θ with respect to y. *Right: Illustration depicting the θ-dependent focal length of light transmitted through the metalens.*

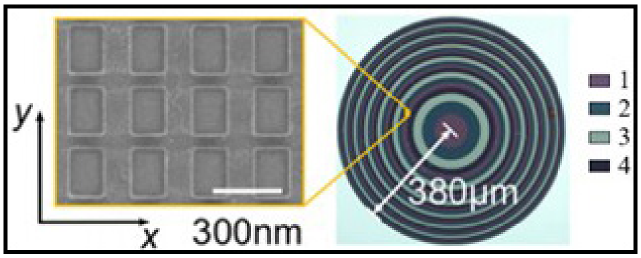

Figure 3: Left: A SEM image of the first metalens subzone. Right: Optical microscope image of the fabricated spherical metalens. The different shades of the metalens correspond to its four different metasurface geometries.

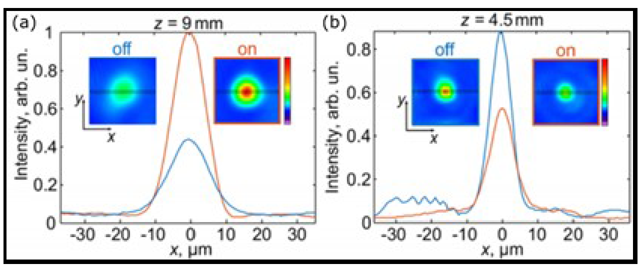

Figure 4: Experimental voltage-dependent focal spot profiles of the metalens (a) Intensity linecuts of the z = 9 mm focal spot image at the 'off' and 'on' voltages of 2.2V_{pp} and 9.8V_{pp}, respectively. The insets show the respective camera images. (b) Same as (a), but for z = 4.5 mm.

voltage-dependent optical axis orientation angle θ of the LC molecules, as depicted in Figure 2. The metalens exploits the electro-optic properties of LCs to tailor the local phase response of the silicon meta-atoms, resulting in continuous and reversible modulations of the metalens focal length.

For the design of a switchable-focus LC metalens, we present a metasurface unit cell template consisting of rectangular silicon pillars encapsulated in a nematic LC between two conductive plates, as shown in Figure 2. The meta-atom geometries are optimized to impart phase shifts to achieve the required hyperbolic phase profile for a spherical lens with focal distance $f = f_{off}$ for $\theta = 0°$, while simultaneously engineered to impart the phase profile of a lens with $f = f_{on}$ for $\theta = 90°$. Therefore, this selection enables voltage-controlled switching between two discrete focal distances of the lens.

We validate this concept by designing and fabricating a 2D metalens that emulates a transition between two distinct concave lenses with focal lengths of f_{off} = 9 mm and f_{on} = 4.5 mm, respectively. Figure 3 shows an SEM image of the fabricated lens. The experimental focal spot tuning is shown in Figure 4. By increasing the AC voltage bias across the LC cell from 2.0V_{pp} ('off') to 9.8V_{pp} ('on'), the focal spot intensity increases by 58% at $z = f_{on}$ and decreases by 37% at $z = f_{off}$.

References:

[1] Soref, Richard. "Mid-infrared photonics in silicon and germanium." Nature photonics 4.8 (2010): 495.

[2] Bosch, M., Shcherbakov, M. R., Won, K., Lee, H. S., Kim, Y., and Shvets, G. "Electrically actuated varifocal lens based on liquid-crystal-embedded dielectric metasurfaces". Nano Letters 21.9 (2021): 3849-3856.