Ultrathin Infrared Photonic Devices Based on Semiconductor-Metasurfaces

CNF Project Number: 2979-21
Principal Investigator(s): Gennady Shvets
User(s): Melissa Bosch

Affiliation(s): School of Applied and Engineering Physics, Department of Physics; Cornell University

Primary Source(s) of Research Funding: Office of Naval Research (ONR), National Science Foundation (NSF)

Contact: gs656@cornell.edu, mb2583@cornell.edu
Website(s): http://shvets.aep.cornell.edu

Primary CNF Tools Used: JEOL 9500, Zeiss Ultra SEM, Oxford 100 Etcher, Oxford PECVD, Woollam RC2 Ellipsometer

Abstract:

Metasurfaces, composed of planar arrays of subwavelength-scale optical antennae, provide tailored resonant modulations to electromagnetic fields. We fabricate semiconductor-based metasurfaces fit for a range of photonic applications in the near-and mid-infrared. For instance, we apply an amorphous silicon (aSi) metasurface to demonstrate an ultrathin wide-aperture multicolor lens. In another application, we exploit tailored field enhancements of silicon-on-sapphire (SOI)-metasurfaces to facilitate deeply-subwavelength femtosecond (fs) laser machining.

Multicolor aSi-Metalens:

Modern imaging systems rely on compact, wide-aperture, and aberration-free lenses. Although submicron-thick optical metasurfaces have achieved high-performance focusing [1], they exhibit high chromatic aberrations, making them unsuitable multicolor imaging applications. Various approaches to achromatic metalensing have been developed [2], but they are typically limited by computational complexity or low numerical aperture (NA). Our project considers a new type of high-NA multicolor metalens, engineered to reuse identical discrete phase requirements in every consecutive 2π phase increment (Fresnel zone) of its phase profile, thereby significantly simplifying its design. To test this concept, we fabricated a spherical metalens with a diameter of 1 mm. Figure 1(a) shows a representative scanning electron microscope of the building blocks of the metalens, which are 600-nm-thick rectangular aSi bricks arranged periodically on a silica substrate. These structures support Mie-type optical resonance modes that can be customized by altering the resonator's geometrical parameters. The metalens comprises only fifteen distinct resonator geometries that are optimized to provide a wavelength- and radially-dependent phase profile resulting in the multicolor focusing of two near-infrared wavelengths. Metalens fabrication consisted of six total steps: plasma-enhanced chemical vapor deposition (Oxford PECVD) of aSi onto fused silica substrate; HSQ-6% spincoat, baking, and electron beam lithography (EBL) exposure at 6mC/cm^2 (JEOL9500FS); development in TMAH/NaCl (0.25/0.7N) salty solution; and pattern transfer to the aSi layer through an inductively coupled HBr plasma reactive ion etch (Oxford Cobra). The resulting samples were characterized using a scanning electron microscope (Zeiss Ultra). Our simulations predict diffraction-limited and chromatic-aberration-free focusing of the two operation wavelengths at a focal distance of $z = 5$ mm. The experimental characterization of our first-generation device shows a primary focal spot at the predicted z-position (5mm) for both wavelengths of light (as shown in Figure 1b). However, there are a few unintended spurious maxima appearing at different z-positions. The production of improved devices is underway.

Subwavelength fs-Laser Nanomachining using SOI-Metasurfaces:

In a second application, we employ tailored electromagnetic field distributions of resonant semiconductor microstructures to enhance the spatial resolution and control of laser-nanostructuring. While laser-machining approaches are typically restricted by the diffraction limit to yield a smallest resolvable dimension equal to half the laser wavelength [3], our project considers deeply-subwavelength-scale (~λ/50) modifications to Si-based microresonators illuminated

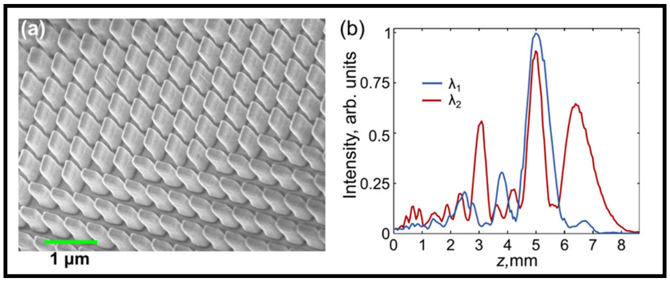

Figure 1: (a) A zoomed-in scanning electron microscopy (SEM) image of rectangular aSi pillars on a silica substrate, comprising the aSi metalens. (b) Experimental on-axis intensity of light transmitted through a first-generation multicolor aSi-metalens. The lens focuses wavelengths of λ_1 = 980 nm (blue line) and λ_2 = 735 nm (red line) into a primary intensity maximum at z = 5 mm.

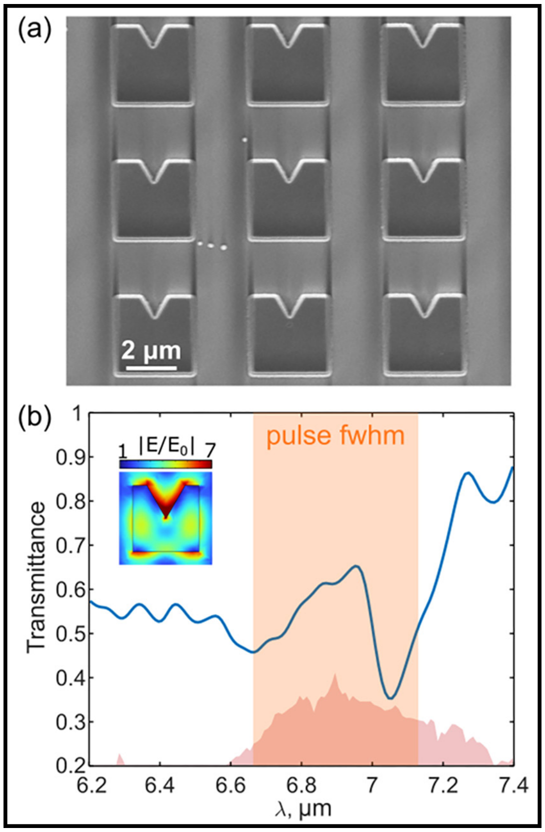

Figure 2: (a) SEM image of a SOI-metasurface designed to enhance the field intensity at the apex of its triangular notch. (b) Representative experimental transmission spectra of the metasurface. Inset: simulated electric field profile of the resonator.

by fs laser pulses. We accomplish this result by designing SOI metasurfaces that resonate near the laser wavelength and exhibit highly-nonlinear photoinduced free carrier production. Illuminating the Si-resonators with few-pulse trains below the single-pulse damage threshold facilitates localized phase explosions and gradual volumetric material ablation in the region of peak field intensity. For device fabrication, we start with the RIE etching of a commercial SOI wafer to the desired thickness, followed by a standard PMMA spin-coat, baking, EBL exposure at 900 μC/cm^2 (JEOL 9500FS), development in MIBK:IPA 1:3 for 90s, e-beam evaporation of 30 nm chromium (Cr) or 80 nm alumina hard mask (CVC SC4500), liftoff in room-temperature sonicated acetone for 30 min, RIE etching to substrate; and removal of Cr or alumina mask by wet etchant. Figure 2 presents an SEM image of the fabricated metasurface prior to laser irradiation alongside its experimental transmission spectra. Figure 3 shows examples of nanotrench formation under various conditions of laser pulse intensity and number.

References:

[1] Pan, Meiyan, et al. Light: Science & Apps 11.1 (2022): 195.
[2] Wang, Shuming, et al. Nature Nanotech 13.3 (2018): 227-232.
[3] Perry, M. D. et al., Journal of Applied Physics 85, 6803 (1999).

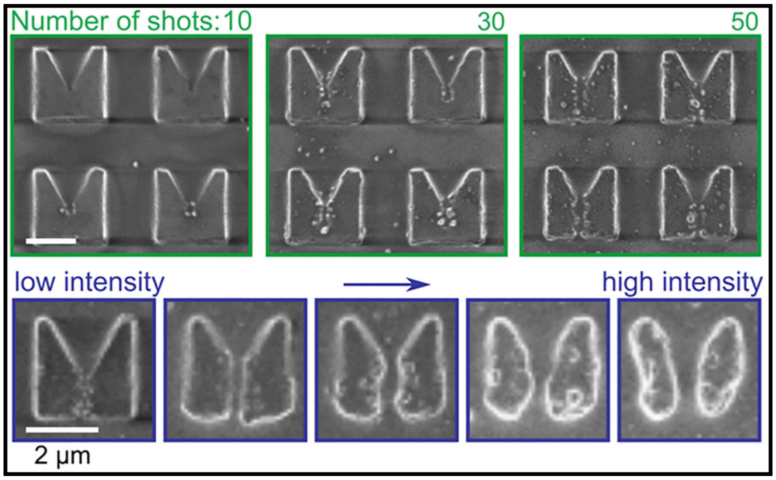

Figure 3: Trench formation in SOI-resonator arrays illuminated with variable (a) shot-numbers and (b) intensities of 7 µm-wavelength incident laser pulses, increasing from left to right.