Ultrathin Infrared Photonic Devices Based on Semiconductor-Metasurfaces

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Abstract:
Metasurfaces, composed of planar arrays of sub-wavelength-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 $2\pi$ 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 ($\sim\lambda/50$) modifications to Si-based microresonators illuminated
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:

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 \( \lambda_1 = 980 \text{ nm} \) (blue line) and \( \lambda_2 = 735 \text{ nm} \) (red line) into a primary intensity maximum at \( z = 5 \text{ mm} \).

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.

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.