Fabrication, Characterization, and Application of All-Glass, 1 cm Diameter Metalens Working at Visible Wavelength

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Primary CNF Tools Used: Heidelberg DWL2000, HamaTech mask chrome etch 1, ASML 300C DUV stepper, Gamma automatic coat-develop tool, CHA Mark 50 e-beam evaporator, Trion Minilock III ICP etcher, Plasma-Therm dual chamber 770, Oxford 81, Oxford 82, Oxford 100, P10 profilometer, DISCO dicing saw, Zeiss Ultra SEM

Abstract:

Using deep-ultraviolet (DUV) projection lithography, we demonstrate mass-production of one-centimeter diameter, all-glass metalenses working in the visible wavelength. Characterization of the metalens by comparing its point-spread-function with that of the ideal lens and conventional refractive lenses with similar size and focal lengths are performed.

Summary of Research:

Recent advances in aerial drones and cube satellites have increased the demands for better optics for their on-board imaging systems. One of the approaches for better imaging is increasing the amount of light collected into the system by increasing the diameter of the lens. However, increasing the diameter of the lens meets two important tradeoffs for their application purposes: the increase of aberration and the weight of the lens. Simply increasing the diameter of a refractive lens increases the spherical aberration, which then needs to be corrected by using costly methods such as tailoring the lens surface to an aspheric. Also, the weight of the bulk refractive optics volumetrically scales with diameter, which renders it less advantageous when payload is of a concern.

Metasurfaces, a new category of optical elements that can tailor the optical effects of the outgoing light by placing subwavelength-spaced structures on a two-dimensional surface, can provide alternative solutions for refractive optics [1]. Although many prior metasurface works used high-refractive index materials such as TiO_2, SiN, GaN or amorphous Si to achieve phase control [1,2], here we use low-refractive index material, fused silica (SiO_2), as a base material to design and fabricate a centimeter diameter metasurface functioning as a lens (metalens) working in the visible wavelength.

We fabricate the metalenses on a 4-inch fused silica wafer using DUV (248 nm, KrF) projection lithography. After writing a reticle of the metalens with Heidelberg DWL 2000 mask writer, the pattern on the reticle is exposed onto the chrome (100 nm thick)-coated fused silica substrate spin-coated with DUV-24P ARC and UV210 resist. The patterned resist is then used as an etch mask to transfer the pattern to the chrome layer using chlorine plasma. As chlorine etch chemistry has high selectivity against SiO_2, the substrate works as an etch stop layer. With the patterned chrome as etch mask, we then etch into the SiO_2 substrate using fluorine plasma. The fluorine etch chemistry has high selectivity between chrome and SiO_2, which allows high-aspect ratio etching of SiO_2. The fluorine etching is stopped when the etch depth reaches 2 µm, which is determined by surface profilometry. The residual chrome is then etched away using chlorine plasma, leaving only SiO_2 pillars on the substrate. The schematic of the process is depicted in Figure 1, and the scanning electron microscope imaging result of fabricated SiO_2 pillars is shown in Figure 2.

The fabricated metalens is capable of imaging in the visible wavelength, as shown in Figure 3. We further compare the metalens' point-spread-function along its optic axis at metalens' design wavelength (λ = 633 nm) with similar off-the-shelf refractive lens counterparts with similar diameter and focal length; an aspheric lens (Edmund Optics, 33-944) and a plano-convex lens (Thorlabs Inc., LA1213-A). As shown in Figure 4, the fabricated metalens show good focusing around its focus compared to that of the refractive optics. The Strehl ratio of the metalens' focal spot is measured to be 0.95, which indicates the fabricated metalens is diffraction-limited. The results are published to Nano Letters [3].

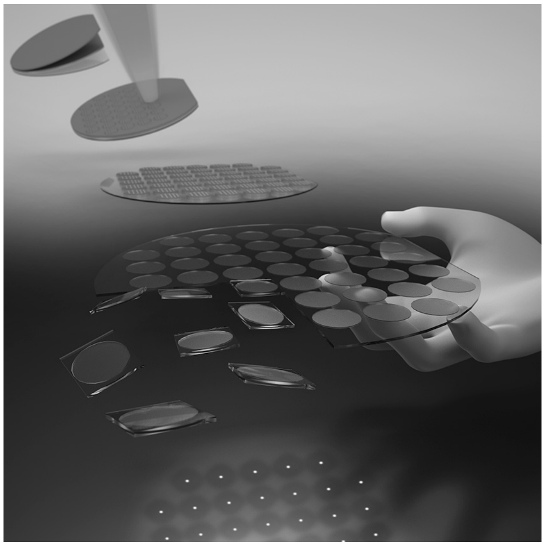

Figure 1: Schematic of fabrication process. A 4-inch diameter fused silica wafer goes through metal evaporation, DUV projection lithography, etching, and dicing to make 45 1-centimeter diameter metalenses per wafer.

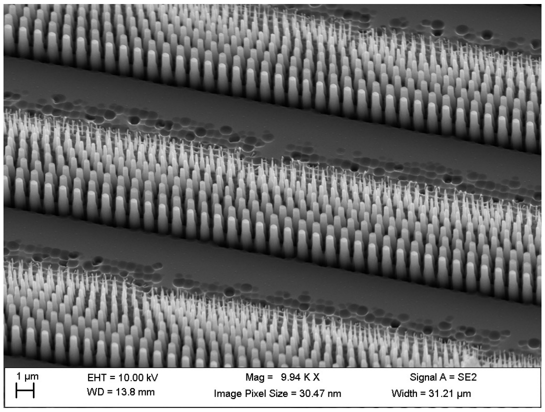

Figure 2: SEM image of silica nanopillars constituting the fabricated metalens.

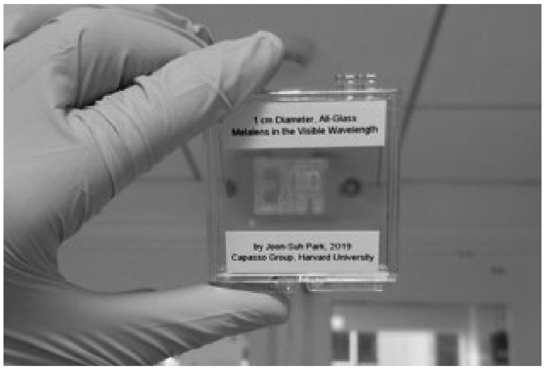

Figure 3: Photograph of a metalens, diced to a 11 mm × 11 mm square from initially fabricated 4-inch wafer, imaging a red-lit emergency exit sign. The image of the "Exit" sign is clearly visible through the metalens.

Conclusions and Future Steps:

We demonstrated a proof-of-concept mass-manufacturing of centimeter-scale metalens working in the visible wavelength and showed that it does not experience spherical aberrations as its refractive counterparts. However, our metalens is chromatic by design: the focal length varies with incident wavelength. We are investigating methods to design and fabricate a larger diameter metalens and an achromatic metalens that is compatible with conventional integrated circuit chip fabrication techniques.

References:

[1] Alan She, Shuyan Zhang, Samuel Shian, David R. Clarke, and Federico Capasso, "Large area metalenses: design, characterization, and mass manufacturing," Opt. Express 26, 1573-1585 (2018).

[2] Mohammadreza Khorasaninejad, Wei Ting Chen, Robert C. Devlin, Jaewon Oh, Alexander Y. Zhu, and Federico Capasso, "Metalenses at visible wavelengths: Diffraction-limited focusing and subwavelength resolution imaging," Science 352, 1190 (2016).

[3] Joon-Suh Park, Shuyan Zhang, Alan She, Wei Ting Chen, Peng Lin, Kerolos M. A. Yousef, Ji-Xin Cheng, and Federico Capasso, "All-Glass, Large Metalens at Visible Wavelength Using Deep-Ultraviolet Projection Lithography," Nano Lett. 19, 12, 8673-8682 (2019).

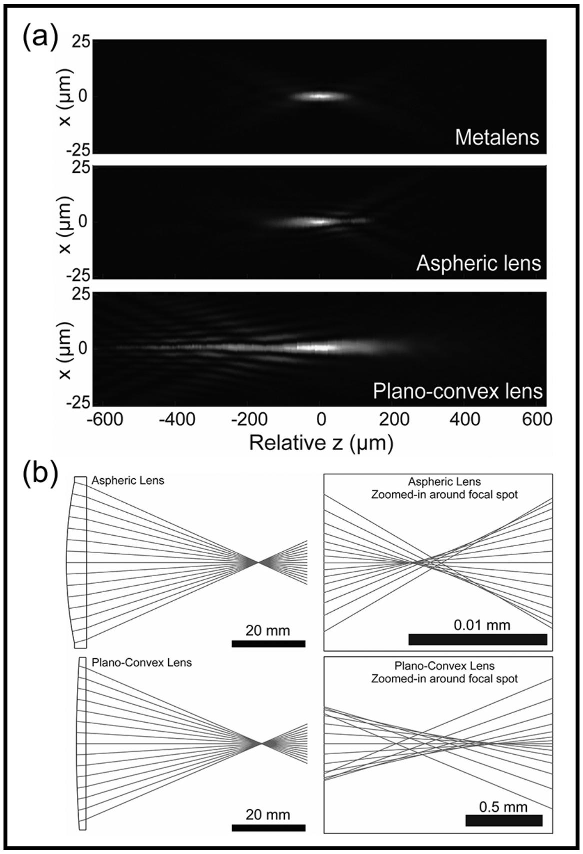

Figure 4: (a) Comparison of point-spread-functions along the optical axis near the focus between a metalens, an aspheric lens (Edmund Optics, 33-944), and a plano-convex lens (Thorlabs Inc., LA1213-A), respectively, with 633 nm wavelength incidence. The refractive lenses are off-the-shelf commercial glass lenses with similar diameter and focal length with those of the metalens. (b) Ray-tracing diagram of refractive lenses derived from data provided by manufacturers.