Three Dimensional Optical Metasurfaces using Two-Photon Lithography

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Optical metasurfaces, nearly planar arrays of subwavelength structures, have rapidly impacted almost every optical function including imaging, filtering, polarization control, and generation of structured light. Metasurfaces simultaneously offer size, weight, and cost reductions compared to bulk optics while often improving performance and enhancing functionality. Most metasurfaces are designed using structures with high refractive-index contrast between the patterned elements and surrounding materials. Here we discuss alternative metasurface designs employing lower refractive-index contrast systems. These 2.5- and 3- dimensional structures retain the size and weight advantages of conventional metasurfaces but can be 3D printed using two-photon lithography. Those without reentrant features are also suitable for replication by molding. In several cases, hybrid metasurfaces have been developed that also exploit refractive and diffractive effects.

First, we will review our group's recent progress in polymer-based, broadband achromatic metalenses. These metalenses use hybrid surfaces with variable-height pillar[1] and hole arrays[2] as shown in Figure 1. We will also discuss 3D printed, two-element, metasurfaces for higher-NA achromatic[2] and variable focal length imaging[3] as illustrated in Figure 2. The latter device will ultimately require mutual rotation of the elements for full functionality, and we will describe some challenges associated with 3D printing mechanical actuators. Finally, we will discuss hybrid metasurfaces for simultaneous optical focusing and filtering[4] and report new results on their application as color-filter arrays for wide-color-gamut imaging as shown in Figure 3. Thus, we will to provide both an overview of recent efforts at the intersection of metasurfaces and two-photon lithography and a preview of future pathways for investigation in this area.

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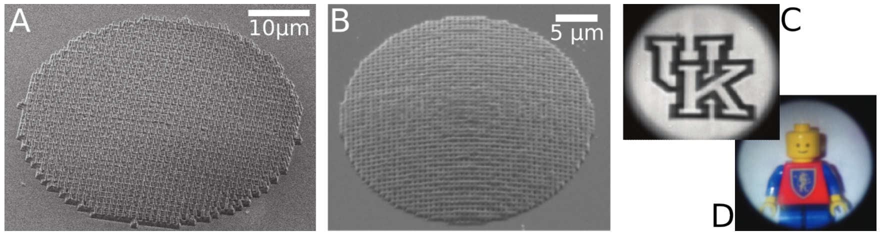

Figure 1: Examples of achromatic metalenses using (A) pillars and (B) holes. (C,D) Example broadband images acquired with metalenses (D) short-wave infrared (1000–1700 nm) and (E) visible (450-700 nm)[1, 2].

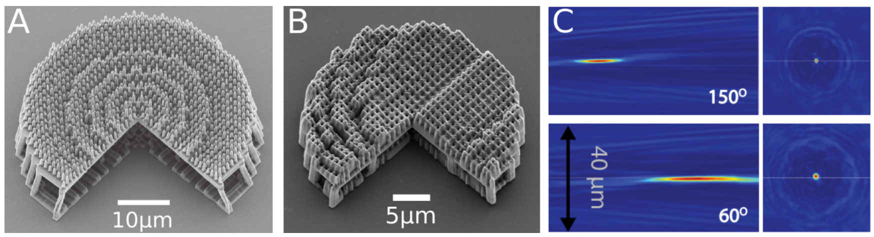

Figure 2: Examples of two-element metalenses fabricated by two-photon lithography. (A) Achromatic metalens operating from 1000 to 1800 nm.[1] (B) Metalens with a focal length that can be tuned by mutual rotation of the two elements. (C) Experimentally measured intensity ($\lambda = 1500$ nm) in the tangential (left) and focal (right) planes at two different rotation angles demonstrating variable focal length.[3]

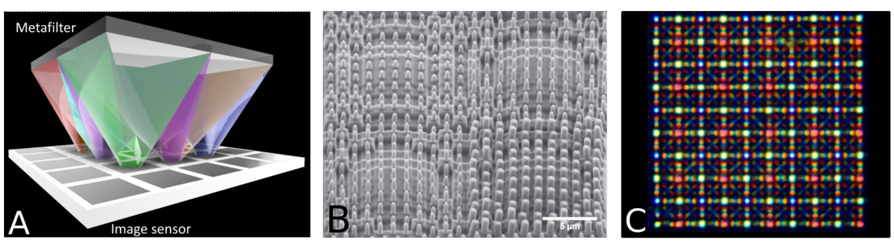

Figure 3: Metasurfaces can provide simultaneous focusing and filtering for wide-color gamut imaging. (A) Illustration of metafilter array matched to an image sensor pixel array. (B) A 2×2 metafilter superpixel designed to map to 3×3 image sensor pixels. (C) Detected signal from a 10×10 array of metafilters.

[1] F. Balli et al., "A hybrid achromatic metalens", Nat. Comm. **11** (2020).
[2] F. Balli et al., "An ultrabroadband 3D achromatic metalens", Nanophotonics **10**, 1259–1264 (2021).
[3] F. Balli et al., "Rotationally tunable polarization-insensitive metasurfaces for generating vortex beams", in Metamaterials, Metadevices, and Metasystems 2020, Vol. 11460 (), pp. 66–73.
[4] M. Sultan et al., "Hybrid metasurfaces for simultaneous focusing and filtering", Opt. Lett. **46**, 214–217 (2021).