Extended Depth of Focus Metalenses for Achromatic Computational Imaging

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Abstract: We demonstrate high-quality, full-color imaging using extended depth of focus (EDOF) metalenses and computational reconstruction. We use rotationally symmetrical phase masks to mitigate asymmetrical artifacts found in the traditional cubic EDOF systems.

Metasurface optics have demonstrated vast potential for implementing traditional optical components in an ultra-compact and lightweight form factor. Metasurfaces, however, suffer from severe chromatic aberrations, posing serious limitations on their practical use. Existing approaches for circumventing this involving dispersion engineering are limited to small apertures and often entail multiple scatterers per unit cell with small feature sizes.

Recently, full-color imaging in the visible wavelength regime was demonstrated using an EDOF metasurface and post-processing deconvolution [1]. This technique relies on a rectangularly separable cubic phase mask (CPM) [2] added to the standard hyperboloidal metalens phase, generating a non-rotationally symmetric extended focal spot. The longitudinally extended nature of the focal spots at different wavelengths is sufficient to compensate for the chromatic shift in the focal length. The CPM is limited, however, in that it produces a transversely asymmetric point spread function (PSF) that makes imaging sensitive to the orientation of the element. Additionally, the CPM produces a lateral shift of the PSF with a change in wavelength, which can contribute to distortions in imaging.

In this paper [3], we extend the family of EDOF metasurfaces beyond a simple CPM to overcome its aforementioned limitations. We design and fabricate four different types of EDOF metasurface lenses operating in the visible range, including both rotationally symmetric and asymmetric phase profiles. Full-color imaging in the visible range is achieved using these EDOF lenses, outperforming the traditional metalens in terms of chromatic aberrations. The four different EDOF lenses (Fig. 1) are, namely, cubic [2], shifted axicon, log-asphere [4], and SQUBIC [5] lenses. All, except for the cubic, are axially symmetric. We fix the aperture for each of these metasurfaces at 200 μm and select a nominal focal length of 200 μm, making the numerical aperture (NA) close to 0.45 for all designs.

These EDOF lenses are then implemented using cylindrical Si3N4 nanopillars to ensure polarization insensitivity. These nanopillars are arranged on a square lattice. By varying the diameters of these nanoposts, the transmission coefficient imparted on incident light is modified as the coupling to and amongst different supported modes by the nanoposts changes, resulting in different phase shifts. Rigorous coupled-wave analysis (RCWA) is used to construct a library consisting of the diameters of the nanoposts and the corresponding phase shift and amplitude.

A comparative analysis of all these lenses is provided, evaluating in terms of optical bandwidth and image quality. We characterize the modulation transfer function (MTF) for all these lenses and demonstrate full-color imaging. We calculate the MTF of all metasurfaces at the nominal focal plane. We find that the MTF of an ordinary metalens preserves spatial frequency information for green light (when focused at the sensor plane) but fails to preserve high frequency components for blue or red. On the other hand, EDOF metasurfaces retain a broad range of spatial frequencies, exhibiting a higher cutoff frequency than the standard metalens. All our EDOF metasurfaces demonstrate at least an order of magnitude larger optical bandwidth compared to a standard metalens.

We then characterized the experimentally captured images, by calculating the SSIM for the “ROYGBVWG” image shown on Fig. 2A. We find that the scores on the devices with EDOF properties are significantly higher than that of the standard metalens.
Fig. 1. EDOF Metasurface Design and Measurements. (A) The phase masks of an ordinary metalens and four different EDOF metasurfaces. (B) Scanning electron micrographs of the fabricated metasurfaces. Inset shows the pillar distribution. (C) We experimentally measured the intensity along the optical axis where from top to the bottom panel represents illumination by 625 nm, 530 nm, and 455 nm wavelengths. A cross-section on the y-z plane is taken for each of the 3D PSF.

Fig. 2. Imaging performance. Restored images taken from an OLED display of colored letters in ROYGBVWG (A), a colorful neighborhood (B), and vibrant umbrellas against the sky. (C) The scale bar signifies 20 μm. Note that the metalens images are raw and unrestored.

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