Hybrid lenses with metasurface-based correctors for compact optics

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Program: FY21 R&TD Innovative Spontaneous Concepts

Objectives

The objective of this work is to demonstrate hybrid lens in which recently invented metasurfaces are integrated with conventional lens. The resulting hybrid lens will exhibit enhanced imaging performance over the lens itself.

Background:

Lenses are ubiquitous optical elements used to construct a variety of optical systems, such as telescopes for remote sensing imagers and spectrometers. However, conventional lenses suffer from a number of so-called aberrations which dramatically reduce the image quality. The standard method for reducing these aberrations is to cascade several lenses together so that they cancel each other's aberrations. However, cascading of optical elements increases the size, weight and cost of optical systems. Moreover, these elements require precise alignment - something that further increases the complexity and cost. A new approach for lens fabrication, which is based on metasurfaces, has been invented recently. Metasurfaces enable the redesign of optical components into thin, planar and multifunctional elements, promising a major reduction in size and system complexity as well as the introduction of new optical functions. Metasurfaces comprise sub-wavelength scale structures whose optical properties are mainly determined by their geometric parameters rather than by material composition. At the same time, meatsurface-based optics exhibits its own limitations. A very promising approach is to combine conventional lenses and metasurface-based elements to achieve the desired performance. These hybrid lenses have potential to reduce the size, weight and complexity of optical systems while retaining their imaging performance.

Approach and Results:

The objective of this work is to demonstrate that hybrid metasurface-conventional lens will have enhanced performance compared to the conventional or metasufrace lens alone. To achieve this goal, we selected a spherical lens on which the metasurface based corrector is fabricated. The corrective metasurface was designed for a commercially available silicon IR lens (Edmund Optics, diameter, D =25 mm, focal length, f =50 mm, NA=0.25). The metasurface was designed to be fabricated directly on the lens itself (Fig. 1). By utilizing optical design software (CODE V), as well as FDTD software (Lumerical), the metasurface was designed to correct for spherochromatic aberrations (the focus changes as a function of pupil coordinate and wavelength). The metasurface was designed to be fabricated on the curved side of the lens to correct the aberrations in 3.4 - 4.2 μm spectral range. In principle, metasurface can be fabricated on either or both sides of the lens, curved and/or flat, to further improve performance. Here, we selected a more challenging task, fabrication on the curved surface. CODE V was used to evaluate the aberrations present in the original lens design. Spherochromatic aberrations are dominant and they reduce the focusing ability of the lens as shown by the Modulation Transfer Function (MTF) in Figure 2 (left). The MTF of the bare lens (red line) is far from diffraction limited (dotted line). To reduce the aberrations, a corrective metasurface was designed with CODE V to introduce a phase function in the pupil plane. This phase function was optimized for each wavelength using the built-in optimization function with the condition of producing the best focus in the image plane for the wavelengths 3.4 μm, 3.8 μm, and 4.2 μm.

Next, we designed the corrective metasurface using Lumerical software. At this step, we first computed the induced phase delay of nanoposts, which compromise the metacorrector, as a function of nanopost radius. Then, we followed the phase functions in the pupil plane found at the previous step from the CODE V simulation to place a nanopost with defined phase delays (set by the nanopost radious). Figure 2 (right) shows e how the metacorrector improves lens performance. The MTF of the hybrid lens is essentially diffraction limited when the phase achieved by the metasurface was introduced on the lens as evaluated in CODE V.

The final metasurface design consists of nanopillars of varying diameters and the final metasurface design covering the silicon lens contains over 250 million nanoposts. Such large metasurfaces push limits of lithography technology. We developed a compression algorithm to significantly reduce memory usage of the data file by several orders of magnitude. Even so, the software used to convert the mask design to the format used by the e-beam lithography system (.v30) struggled with the number of elements. To resolve this, we had to reach out to the software company and get expert advice on how to make the file conversion. This led to unforeseen delays in the project, but the problem was eventually resolved.

The designed metasurface was fabricated on the curved side of a planospherical silicon lens. In principle, doing e-beam lithography on the curved surface is extremely challenging. However, JPL has previously developed this technology for the curved diffraction grating, that was successfully used in this project. For fabrication, we spinned and baked the negative resists maN-2405 diluted with anisole (1:1 ratio), on the curved surface of the lens. Next, we wrote the metasurface design using an e-beam lithography system. After e-beam exposure, the pattern was developed in AZ MIF300 (Fig. 3). The resist was then used as a mask during a highly selective cryoetch process using SF_6 and O_2, while keeping the substrate at T = -120C. After etching, the resist was removed leaving metasurface pattern on the curved side of the lens (Fig. 3). We are currently testing the fabricated hybrid lens to demonstrate the performance enhancement.

Significance/Benefits to JPL and NASA:

This work is a demonstration of hybrid meta-optical components with enhanced functionality and reduced complexity. This hybrid lens is based on a conventional infrared lens which aberrations were corrected with metasurface fabricated on one of the lens surfaces. These hybrid lenses have potential to reduce size, weight, cost and complexity of future optical systems (e. g. telescope for remote imaging systems) and to enable entirely new functionality such as polarization control.

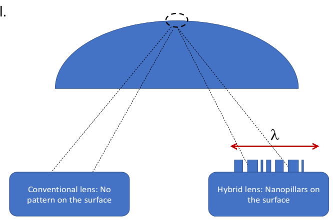

Figure 1*: Comparison between conventional lens (left) and hybrid lens (right). The hybrid lens is compromised from the conventional lens with metacorrector fabricated on the top surface. The metacorrector consists of nanoposts with subwavelengths diameters that impose a varying phase function on the light wavefront. The phase function is designed to correct an optical aberration of the conventional lens.*

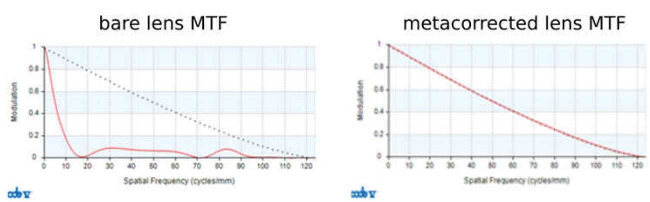

Figure 2: *Modulation Transfer Function (MTF) of the lens without (left) and with (right) metacorrector at wavelength 3800 nm. The red lines denote the calculated lens performance and the dotted lines diffraction limited performance. The metacorrected lens is essentially diffraction limited at 3800 nm.*

Figure 3: *(Left) Photograph of the 1-inch metacorrector pattern written on a silicon lens. (Right) Scanning electron microscope image of the center of the etched metacorrector pattern. The nanopillars visible in the image are approximately 1.6 μm in diameter and etched to a depth of 2 μm.*

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Clearance Number:
RPC/JPL Task Number: R21206