Wavefront Control via Tunable Metasurface

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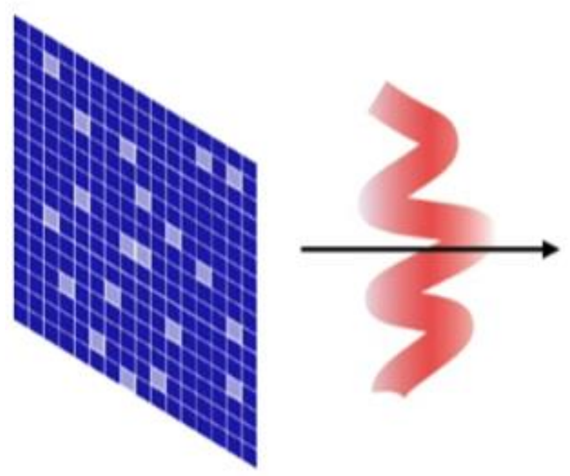
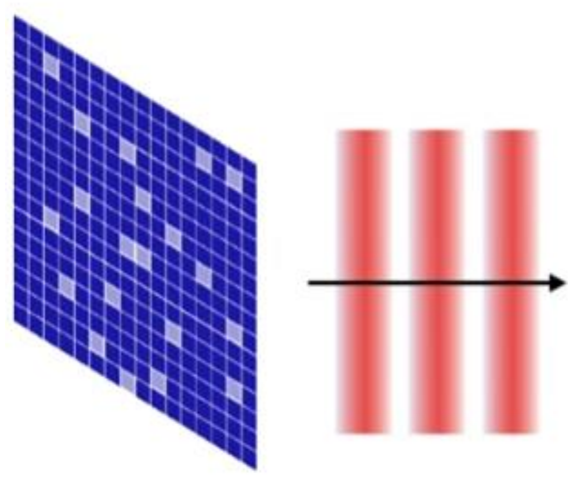
Background

Metasurfaces are two-dimensional (2D) structures that can modify properties of incident light. Comprising subwavelength features, they are primarily used to control wavefronts. The scattered light from such surfaces may have different phases, polarization, angles, etc. Consequently, depending on the arrangement of meta-atoms, characteristics of light at the output can be controlled.

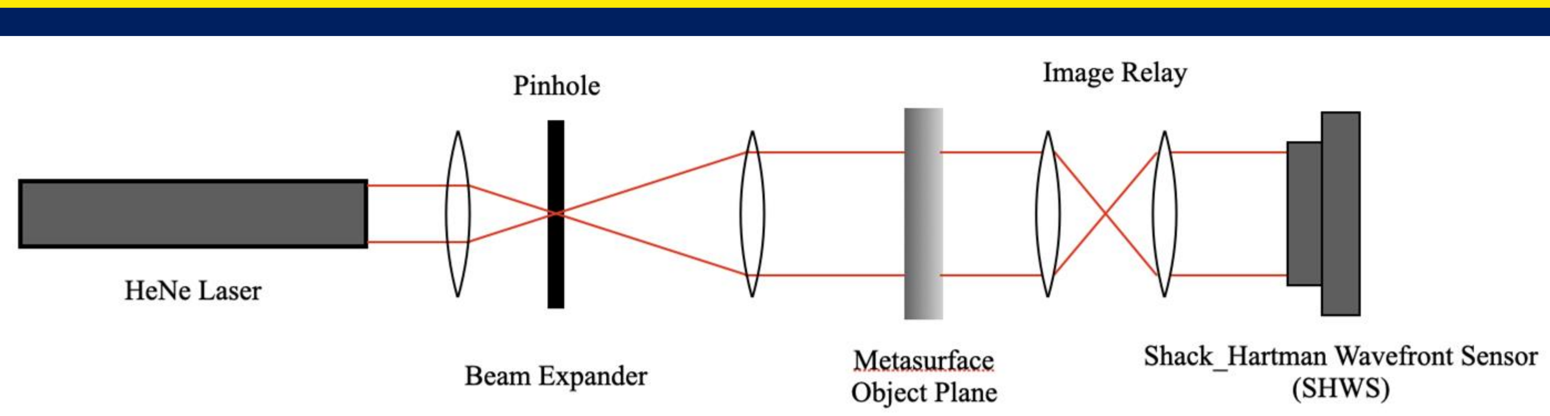


For aberration correction, a local design is required where the phase changes with position. With tunable metasurfaces, an additional medium is used. The orientation of the molecules can thus change according to the electric field applied.

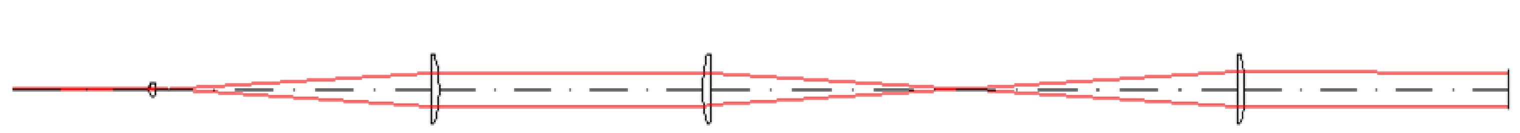


The objective is to design a hybrid system with afocal relays and an active metasurface to mitigate aberrations in the YieldStar sensor. Since they affect measurement reliability, the system wavefront is analyzed as the metasurface is optimized to correct the wavefront deformations.

Optical Design



A beam expander and image relay are designed for a HeNe laser (633 nm). The beam is initially magnified by 20X while the metasurface is then placed at the pupil plane at the end of the beam expander. A spatial filter may also be located at the internal focus point for effective clean up of the beam. It will then be relayed using another afocal telescope before the laser beam is imaged onto the SHWS.

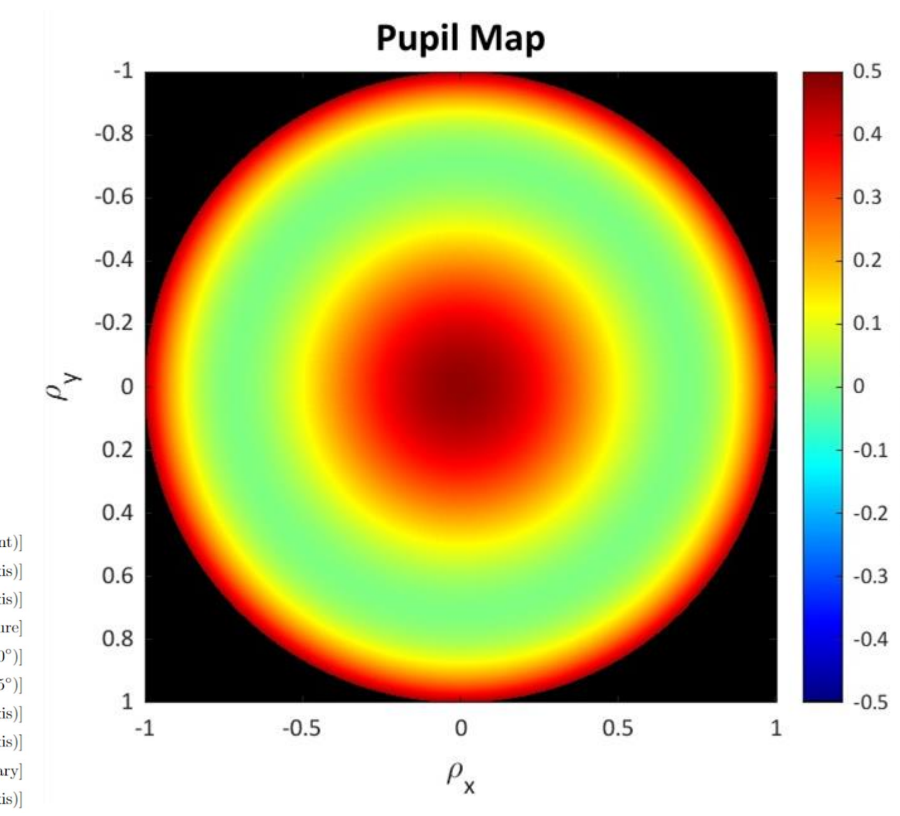


A Keplerian Telescope design, which has an intermediate focus, is utilized for the design due to low laser power. Using off the shelf optics, focal lengths of 4 mm and 80 mm are selected for the objective and eyepiece respectively. The image relay is based on a 4f optical system. Thus, the second lens of the beam expander is replicated for the image relay. It contains a magnification of 1X. The test stand withstands 0.142 waves of optical aberrations.

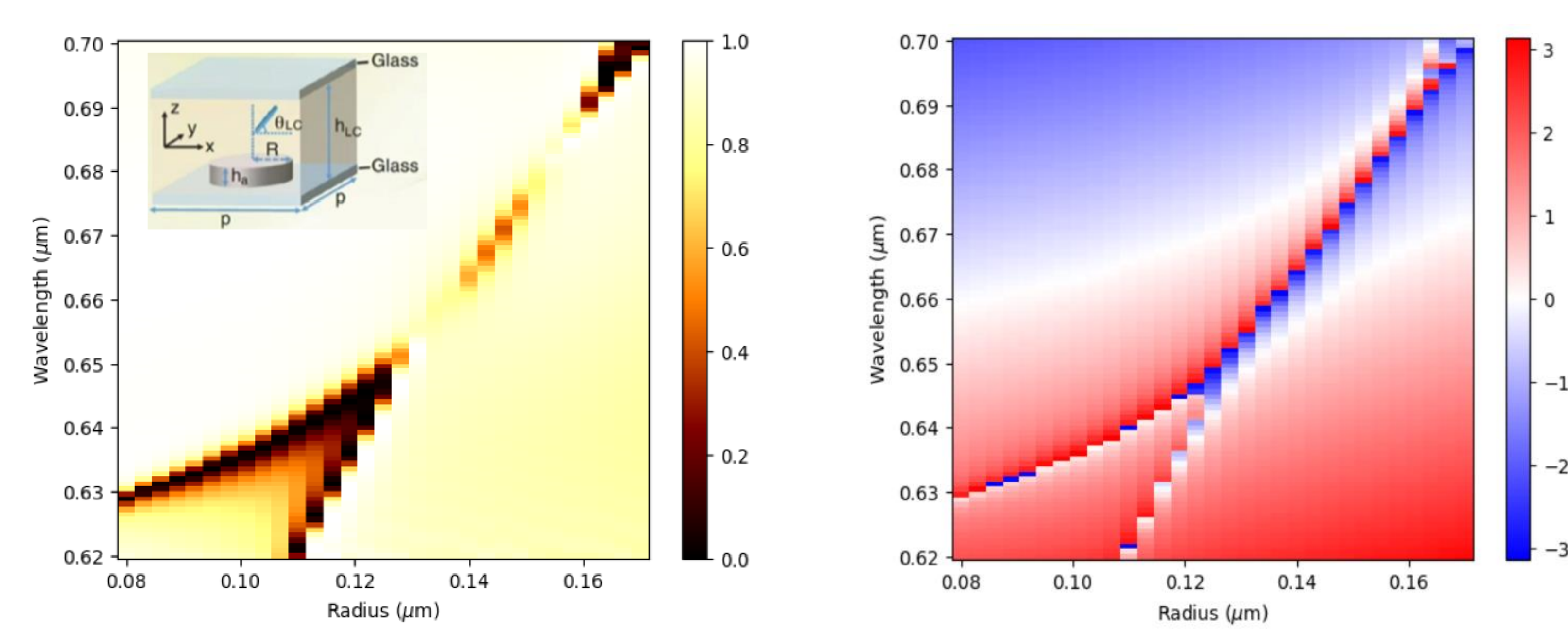
Pupil Map Reconstruction

Using the Zernike Coefficients exported from CodeV, the pupil map can be reconstructed in MATLAB. This dictates the target metasurface design. As shown in the map, the system contains different orders of spherical aberration and defocus.

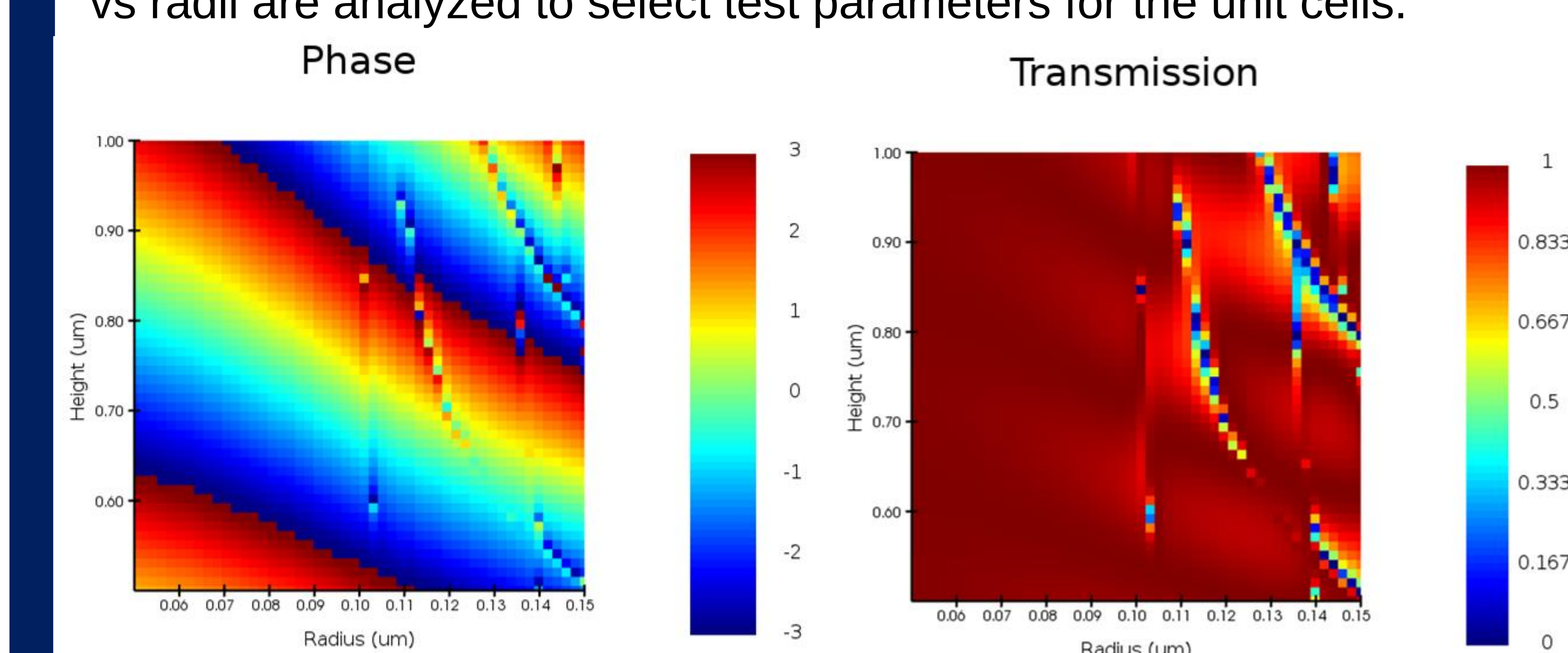
1. $Z_1 = 1$ [Piston (constant)]
2. $Z_2 = R\cos\theta$ [Distortion - Tilt (x-axis)]
3. $Z_3 = R\sin\theta$ [Distortion - Tilt (y-axis)]
4. $Z_4 = 2R^2 - 1$ [Defocus - Field curvature]
5. $Z_5 = R^2\cos(2\theta)$ [Astigmatism, Primary (axis at 0° or 90°)]
6. $Z_6 = R^2\sin(2\theta)$ [Astigmatism, Primary (axis at 45°)]
7. $Z_7 = (3R^2 - 2R)\cos\theta$ [Coma, Primary (x-axis)]
8. $Z_8 = (3R^2 - 2R)\sin\theta$ [Coma, Primary (y-axis)]
9. $Z_9 = 6R^4 - 6R^2 + 1$ [Spherical Aberration, Primary]
10. $Z_{10} = R^3\cos(3\theta)$ [Trefoil, Primary (x-axis)]



Meta-Atom Simulation

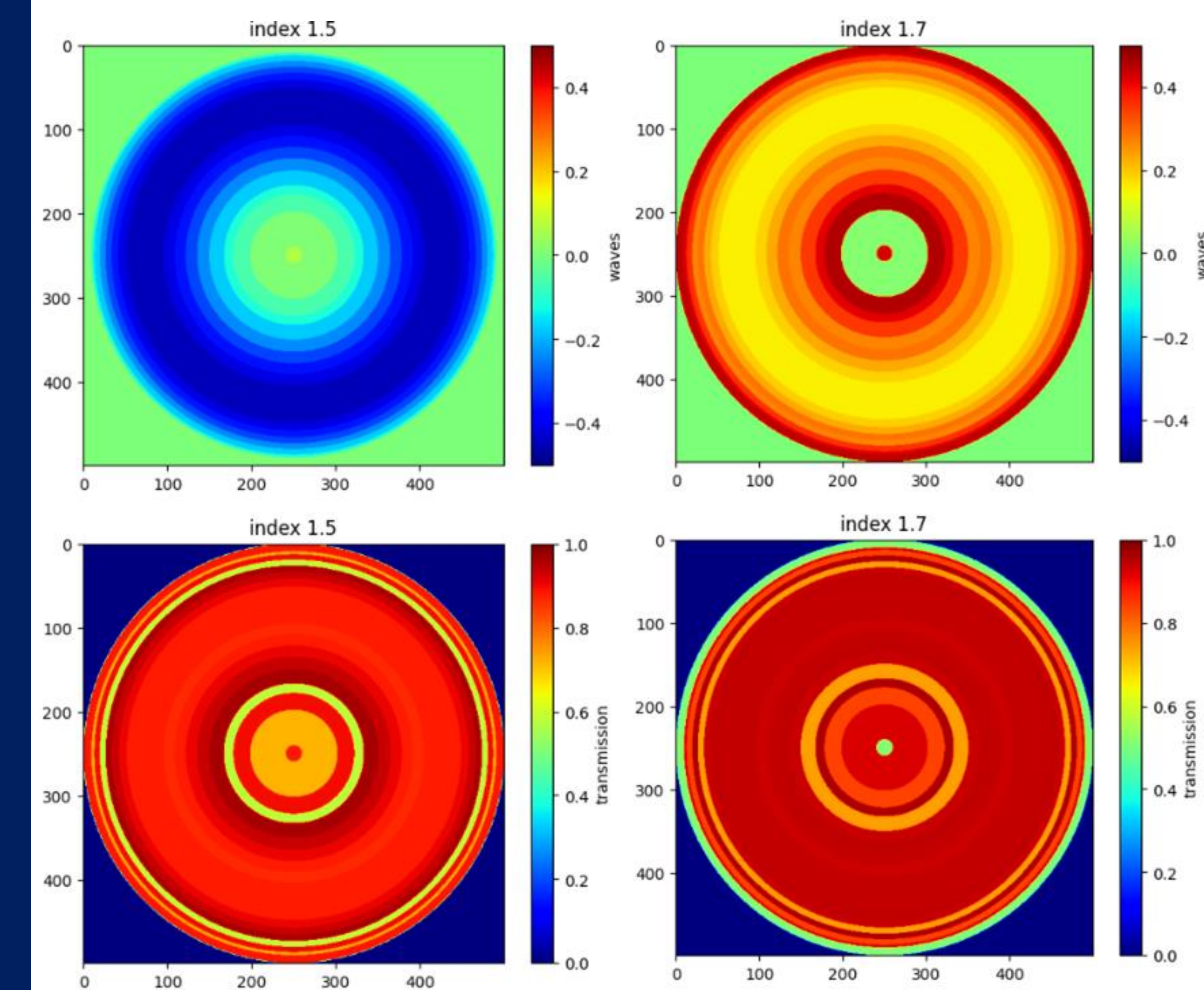


In previous research, a tunable dielectric metasurface was designed, serving as the project starting point. Nanoantennae were integrated with liquid crystals (LC) as the LC orientation change would affect the structural resonance and phase retardation. Plots of the wavelength vs radii are analyzed to select test parameters for the unit cells.



To generate a larger-scale metasurface, the unit cell parameters need to be formally defined. High transmission and a phase change of at least 2π are required. By sweeping the radius and height in the RCWA software of Lumerical, a TiO_2 cylindrical nanorod meeting the criteria is created on a SiO_2 substrate. As height of the nanostructure is crucial for manufacturability, a height of 0.65 μm is selected. The height-to-width ratio is also maintained within a 3:1 to 10:1 ratio.

Metasurface Design



With the system being dominated by spherical aberration, the design is assumed to be rotationally symmetric. Due to hardware limitations in simulating the full-scale metasurface, data points were sampled for the given radius and then recreated for the entire metasurface. The output matches the desired wavefront and successfully corrects existing aberrations. With the liquid crystals and an index of 1.7, the phase profile changes while the transmission remains high.

Conclusions

We have designed an optical system that induces 0.1-0.7 waves of aberrations and an active metasurface that corrects the wavefront error at the desired wavelength. Using the reconstructed phase profile, simulations in Lumerical/Tidy3D modelling the meta-atom and larger-scale metasurface deliver the required wavefront correction with a transmission > 70%.

Acknowledgements and References

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