Design and prototyping of broadband metasurface scalar phase masks for high-contrast imaging

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ABSTRACT

NASA's future Habitable Worlds Observatory (HWO) will enable the direct detection and characterization of Earth-like planets around Sun-like stars using high-contrast imaging. One of the most promising approaches to achieve this goal is to use a coronagraph. A good candidate for implementation in HWO is the vortex coronagraph, which is featured in both earlier mission concepts HabEx and LUVOIR. However, HWO would benefit from a scalar vortex coronagraph instead of the well-established vector vortex coronagraphs in order to reach its ambitious goal of characterizing Earth-like exoplanets. Metasurfaces present a promising technology for achromatizing scalar vortex coronagraphs, because they allow for more design freedom in a single layer of constant thickness compared to scalar vortex phase masks based on variable thickness of a dielectric substrate. Here, we present our progress in developing metasurface scalar vortex phase masks. We present updated broadband designs of scalar metasurface phase masks of different topographies (vortex and phase knife), and simulate their performance with appropriate simulation tools. We also discuss first manufacturing attempts at such masks, and outline the next steps needed to push their performance towards the levels required for HWO.

Keywords: metasurface, scalar vortex, phase knife, nulling, coronagraph, high-contrast imaging, exoplanet

1. INTRODUCTION

The decadal survey of astronomy and astrophysics[1] has identified the characterization of Earth-like exoplanets as a key priority. NASA's future Habitable Worlds Observatory (HWO) will address this goal by directly imaging and characterizing 25 Earth-like exoplanets around Sun-like stars. High-contrast imaging is mandatory to achieve this goal, and a coronagraph is one of the most promising approaches to implement it.

The earlier mission concepts HabEx[2] and LUVOIR[3] both feature a vortex coronagraph of charge 6. This is also a promising candidate for HWO because of its trade-off between inner working angle and sensitivity to low order aberrations. However, the high contrast levels required for HWO are challenging to achieve with current vortex coronagraph technologies. In particular, current vortex coronagraphs[4–6] are vectorial in nature, meaning they exploit the polarization nature of light by imprinting a geometric phase ramp[7,8] onto the beam. Even though these coronagraphs have yielded performance on the order of 2e-9 in 10% bandwidth[9] and effort is put into pushing these masks toward the required HWO performance goal,[10] they suffer from polarization sensitivity. This is typically addressed by filtering only one single polarization, which results in the total throughput being reduced by a factor of 2.

An alternative approach to restore the full throughput is using a scalar (polarization-independent) vortex mask. This approach uses longitudinal phase delays to imprint the characteristic helical phase ramp instead of the geometric phase. However, this concept is inherently chromatic.[11] One way to achromatize scalar vortex

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coronagraphs is to optimize the phase ramp topography,[12] which has led to narrowband contrasts on the order of 1e-8 in lab, and further designs are currently investigated.[13]

We here use a different approach to scalar vortex phase masks using a phase mask made of a single metasurface layer of uniform thickness to imprint the helical phase ramp across a broad band. Metasurfaces are thin structures consisting of subwavelength building blocks in a single layer[14] capable of tailoring phase and transmission response of an incident beam. Metasurfaces have been used to create flat optical devices, such as lenses,[15] wave plates,[16] and vortex beam generators.[17,18] More recently, effort has been put into making these elements achromatic.[19,20] In particular, we have proposed a method to design an achromatic vortex phase mask using a scalar metasurface framework applied to periodic[21] and aperiodic patterns.[22] Here we present updated broadband designs of two metasurface scalar phase masks applicable in the near infrared, one featuring a vortex pattern and one featuring a simpler phase knife consisting of a π-shifted pupil bisector (Sec. 2). We then discuss first manufacturing attempts at the phase knife mask (Sec. 3) and conclude by outlining the next steps needed to push the performance of metasurface scalar phase masks towards the levels required for future high-contrast imaging instruments (Sec. 4).

2. SCALAR PHASE MASK DESIGNS

Following the process described in Ref. 21, we designed a metasurface based on square building blocks arranged in a cartesian grid. We simulate the phase and amplitude response using rigorous coupled-wave analysis (RCWA), which involves periodic boundary conditions replicating a building block in a periodic lattice, and therefore is accurate for relatively smooth metasurface patterns that are locally periodic. The resulting chromatic phase and amplitude response of metasurface building blocks with different geometric parameters can then be used to find an achromatic design. To do so, consider Fig. 1 showing the phase response of an all-silicon metasurface of different block sizes and given height at different wavelengths. The goal is to find a region in this plot where the target phase coverage (2π for the vortex phase mask) is reached for all wavelengths (this is the case between the two vertical dashed lines). We here choose a silicon platform for our metasurface because of its high refractive index (resulting in lower metasurface height and therefore relaxing manufacturing constraints), its transmittance in the near infrared, and the established manufacturing processes inherited from the semiconductor industry.

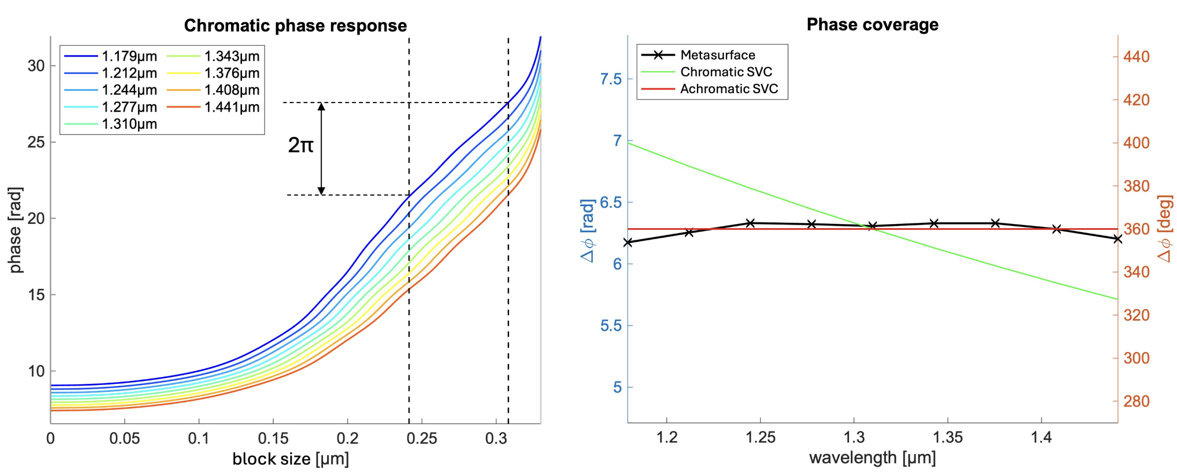

Figure 1. Left: Simulated phase response of all-silicon metasurface of height $d = 1.6\,\mu m$. The phase response is shown against the block size for a metasurface periodicity $\Lambda = 330\,nm$. The curves for 9 wavelengths spanning 20% bandwidth are shown in different colors. The two vertical dashed lines represent the region in the parameter space in which the desired phase coverage of 2π is reached for all wavelengths. Right: Chromatic phase coverage in the highlighted region. The metasurface (black) is much closer to the achromatic phase response (red) than current chromatic scalar vortex designs based on a helical shaped dielectric substrate (green).

The desired range with 2π phase coverage of metasurface building blocks is then used to construct a metasurface design of the vortex phase mask (left part of Fig. 2). This design features very small gaps between the metasurface building blocks. It is worth noting that for one specific wavelength the helical phase ramp could be created using a design with larger gaps and reduced height, which makes the manufacturing process considerably less challenging. However, the small gaps are needed for high performance across a broad band, which is crucial for exoplanet imaging.

Apart from scalar vortex phase masks, the same design framework can be used to create other phase mask topographies, such as the phase knife.[23] The phase knife is a phase mask useful for nulling in the pupil plane, and imprints a π-phase-shifted pupil bisector which effectively nulls the light of an on-axis star. Combined with a single mode fiber it enables the detection of exoplanets at sub-λ/D separations. We here focus on the phase knife for our first metasurface prototype, because of its simple design, consisting of only one π-shifted region implemented with a metasurface. The design of the phase knife and its metasurface analog is shown in the right part of Fig. 2. Note that this design consists of one single metasurface region and is therefore easier to manufacture.

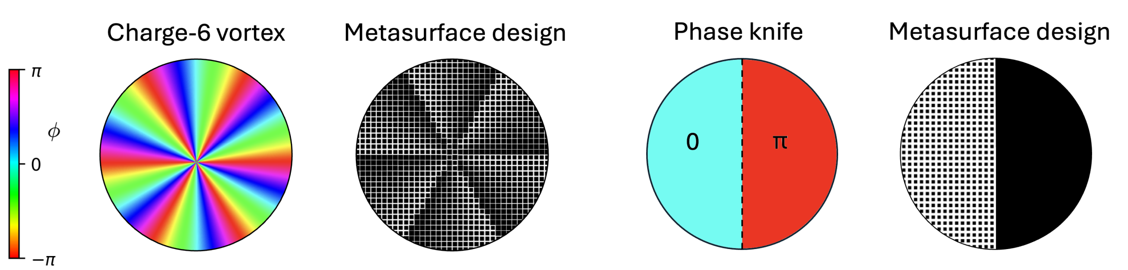

Figure 2. Left: Scalar metasurface vortex phase mask design optimized for a height of 1.7 µm. Right: Scalar metasurface phase knife design optimized for a height of 500 nm.

3. PROTOTYPE MANUFACTURING

In order to provide the desired achromatic phase response the metasurface designs discussed in the previous section rely on building blocks with small gaps between each other. This results in high-aspect ratio structures and can be challenging for precisely manufacturing the metasurface. We therefore start our prototyping efforts by trying a set of small-scale metasurface designs in order to tune the manufacturing process to our desired outcome.

The manufacturing process is based on a pseudo-Bosch process.[24] First a silicon wafer is spincoated with 400 nm of ZEP-520A photoresist. Next the metasurface pattern is written using E-beam lithography and a chromium discharge layer which is removed prior to development with ZED-N50. Finally the sample is etched in a STS Multiplex deep reactive ion plasma etcher using a pseudo-Bosch recipe (SF_6 + C_4F_8). The process results in an etch rate which depends strongly on the gap size between the metasurface blocks and ranges from $100 - 330$ nm/min in our case. The sidewall angle also depends on the gap size but lies consistently between $1°$ and $3°$.

We manufactured a series of small-scale prototypes, aiming to find the right lithography exposure parameters and etching recipe. Fig. 3 (left) shows a scanning electron microscope image of a metasurface prototype with parameters compatible with a phase knife mask applicable to the J-band ($1179 - 1441$ nm, 20% bandwidth). The metasurface has gaps of 117 nm width and a depth of 525 nm with a sidewall angle of $2.0°$. Simulations of this metasurface geometry show that it should provide a π phase shift with deviations $< 0.7°$ across 20% bandwidth (right part of Fig. 3).

This metasurface design will next be used to manufacture a full-size broadband phase knife. The performance of the phase knife is characterized by its capability to reject the stellar light in a cross aperture nulling configuration, which is quantified by the null depth $N \approx \delta\phi^2/4$ where $\delta\phi$ is the deviation from π phase shift. The null depth computed from the simulated phase response is shown in Fig. 4. Note that this result is comparable to

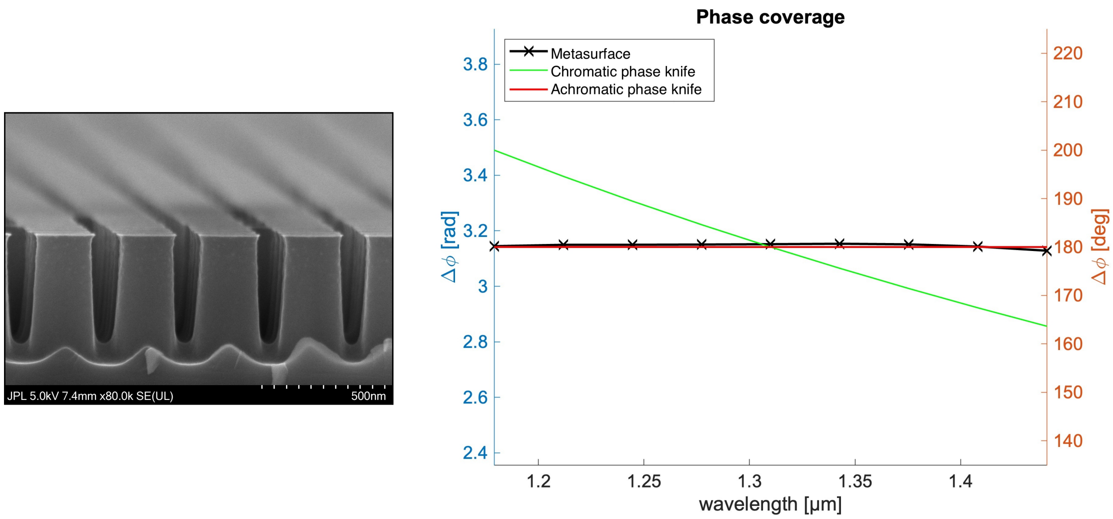

Figure 3. Left: Scanning Electron Microscope image of a metasurface prototype compatible with a broadband phase knife design. The measured metasurface parameters are periodicity $\Lambda = 330nm$, etch depth $d = 525nm$, gap width at top $x = 117nm$ and sidewall angle $\alpha = 2.0°$. Right: Simulated chromatic phase response of the metasurface assuming the measured parameters (black), which is close to the phase required for an achromatic phase knife (red). The chromatic phase response of a phase knife made from a step in a dielectric substrate is shown as comparison (green).

the performance of current phase knife masks that yield null depths on the order of 1e-5. However, our metasurface phase knife reaches this performance across a broad band, showing the potential for making broadband metasurface devices.

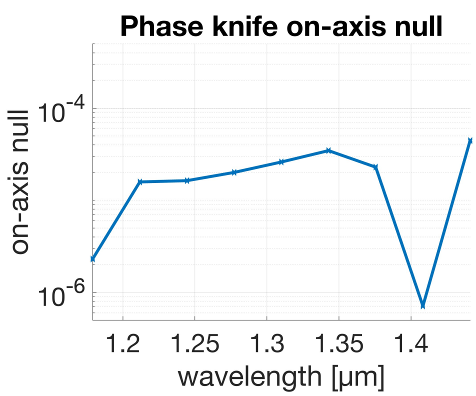

Figure 4. Simulated chromatic null depth of a scalar metasurface phase knife based on the geometric parameters of the metasurface prototype shown in Fig. 3.

4. CONCLUSION

In the context of future space telescope missions, high-contrast imaging and characterization of Earth-like exoplanets is a major goal. We have presented our efforts in achromatizing scalar phase masks for high-contrast imaging using a metasurface framework. The design optimization of metasurface phase masks has shown that achromatic designs require small gaps between metasurface blocks arranged in a square lattice. We have manufactured a series of prototypes with different parameters, and shown that these can be used to manufacture a broadband metasurface phase knife applicable for stellar nulling. The next steps will be to characterize these prototypes in terms of their actual phase response and transmission, and produce a full-size phase knife mask to be tested on our Infrared Coronagraphic Testbed (IRCT).[25] Further, we will push the manufacturing process toward smaller gaps between the metasurface blocks in order to allow more complex designs such as the scalar vortex phase mask.

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