Prospects for Metasurfaces in Exoplanet Direct Imaging Systems: from principles to fabrication

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Motivation

- To reach earth-like ($10^{-10}$) contrasts, direct imaging systems need improvement.
- Metasurfaces can improve these systems at various stages of the optical pipeline!
- Vortex coronagraphs are current state of the art but limited by conventional optics:
  - Vector (VVC) - polarization leakage (Mawet et al. 2005, Mawet et al. 2009b)
  - Scalar (SVC) - highly chromatic (Ruane et al. 2019)
- With metasurfaces, we can design achromatic SVCs and multiplexed VVCs.
What are metasurfaces?

- Arrays of nanoscale structures - very compact
- Can manipulate phase, amplitude, polarization, wavelength very precisely!
- Useful for direct imaging, where control of light is vital
- Can work through many mechanisms - propagation and/or geometric phase, Huygen’s resonances, plasmon resonances, etc.
How do metasurfaces work?

- **Polarization insensitive:** changing shape diameter/spacing at fixed height changes effective refractive index $n_{\text{eff}}$

- Unit cell: nanostructure + patch of substrate

- Arrange unit cells according to their behavior and desired optical behavior

Relevant review papers: Kamali et al. 2018, Neshev and Aharonovich 2018, Lee et al. 2020, Hu et al. 2021
How do metasurfaces work?

- **Polarization sensitive**: changing shape side lengths/spacing at fixed height changes $n_{\text{eff}}$ differently for $\perp$ polarizations.

- **Unit cell**: 

- **Optical behavior** can be different for $\perp$ polarizations.

Arbabi et al 2015
How do you design a metasurface?

Simplest way: forward design

![Graph showing phase (rad) vs radius (µm)]
How do you design a metasurface?

My method: fast, robust optimization built off of forward design
How do you design a metasurface?

Preliminary Considerations:

- Materials
- Fabrication constraints

a-Si on glass
Metasurface Optimization: FDTD Sweep

Diameter

Also sweep other shapes

Period

Transmission

Phase (rad)

Shape Width (µm)

Period (µm)
Metasurface Optimization: Clocking Optimization

\[ \lambda_1, \lambda_2, \lambda_3 \]

Ideal Phase (rad)

\[ \text{CLOCKING} \]

\[ -\pi, \pi \]

Phase

\[ \lambda_1, \lambda_2, \lambda_3 \]
Metasurface Optimization: Nanostructure Selection

Chosen unit cells:

![Diagram showing nanostructure selection with phase residuals and transmission plots.

- Diameter
- Period
- Phase
- Residuals
- Transmission

λ

Phase (rad) 2π

0

λ

λ

λ
Metasurface Optimization: Profile Mapping
Metasurface Optimization: Aperiodicity

- Arbitrary aperiodic metasurfaces have never been demonstrated to our knowledge
- We show that this technique can be used for achromatization of metasurfaces (paper coming soon!)
- Unit cells arranged using meshing software DistMesh (Persson et al. 2004)
How do you design a metasurface?

My method: fast, robust optimization that works better than forward design.
We design J, H, K, and V metasurface scalar vortices (MSVs) operating over 15-20% bandwidth.

J, H, and K designs have features compatible with photolithography.
V-band charge-6 metasurface (simulated) performance
V-band charge-6 metasurface (simulated) performance

- 548nm
  - RMS = 0.03
  - $T_{avg} = 93.8\%$

- 565nm
  - RMS = 0.04
  - $T_{avg} = 94.4\%$

- 604nm
  - RMS = 0.04
  - $T_{avg} = 95.0\%$

- 649nm
  - RMS = 0.02
  - $T_{avg} = 94.3\%$

- 673nm
  - RMS = 0.02
  - $T_{avg} = 95.4\%$

- 700nm
  - RMS = 0.05
  - $T_{avg} = 95.5\%$
Optimized metasurface (simulated) performance

Try two metasurface scalar vortex designs:

- conventional charge 6
- cosine charge 6

(Ruane et al. 2019)

Contrast between $3 \times 10^6$

Graph showing contrast vs. phase scale factor.

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Contrast

Try two metasurface scalar vortex designs:

- conventional charge 6
- cosine charge 6

(Ruane et al. 2019)
Using multiple nanostructure shapes and variable spacing, we improve achromatic performance compared to conventional SV’s. We expect to get deeper contrasts as we expand our unit cell shape library and/or use a multi-layer platform.
Optimized metasurface (simulated) performance

Vortex Fiber Nulling

Our simulated K-band charge-1 vortex beats theoretical null depth
Optimizing a Polarized metasurface

- I have added polarization dependent functionality to my optimization - here's some preliminary H-band results!
Achromatizing a Polarized metasurface

- A preliminary z-band example:
  - For this phase data (only 1 wavelength pictured)
  - Get this simmed performance

Pol 1

- \( \lambda = 900.0 \text{ nm} \)
- \( \lambda = 930.0 \text{ nm} \)
- \( \lambda = 950.0 \text{ nm} \)

Pol 2

- \( \lambda = 980.0 \text{ nm} \)
- \( \lambda = 1000.0 \text{ nm} \)
We (so far) use a photolithography based platform with a-Si structures on SiO$_2$ substrate. An electron-beam lithography (EBL) process would be very similar!
Preliminary Fabrication Results

- As we perfect our achromatic designs, we have begun refining our fabrication process with simple, one-shape metasurface vortices.
Metasurface characterization

- Want phase and amplitude behavior? Use a Digital Holographic Microscope (DHM, Wallace et al. 2015)!
Preliminary Characterization Results

Very over-etched sample

Too tall!

Poorly-etched sample

Too wide!

Phase (rad)

2π

0
Next Steps

- Continue fabrication and characterization of achromatic designs
- Continue investigating contrast behavior of my vortex designs
- Improve current designs with EBL sized features and more exotic frameworks
Phase

MSV (SEM image)

Collimating lens

Objectives

Relay lens

Camera

SMF

Blank Substrate

Phase

Amplitude

Preliminary H-band DHM data for an MSV