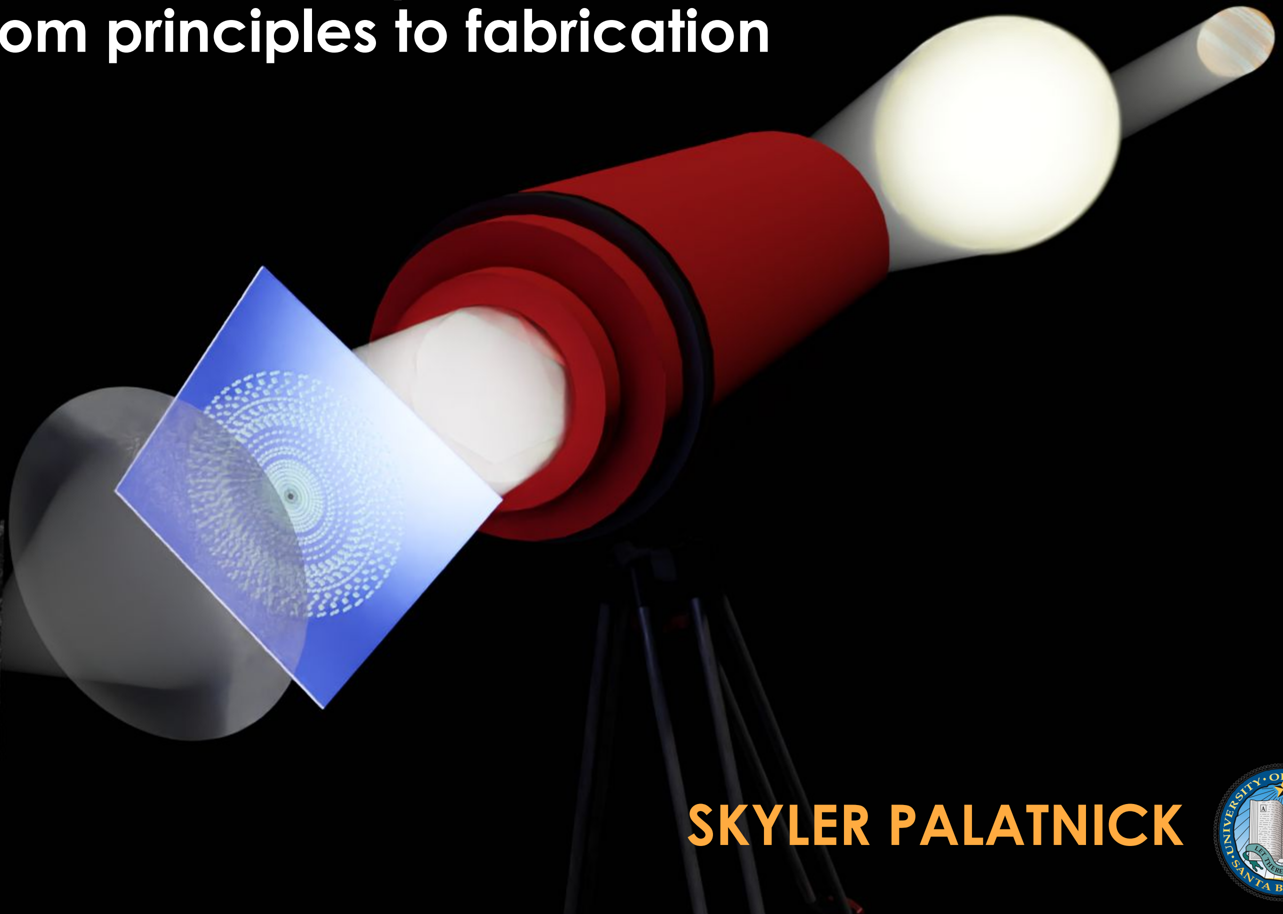
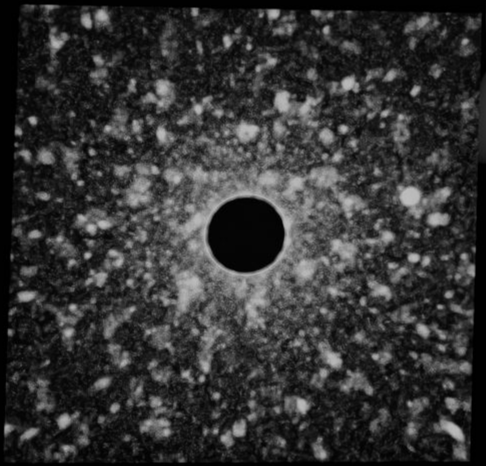
Prospects for Metasurfaces in Exoplanet Direct Imaging Systems: from principles to fabrication





SKYLER PALATNICK

Lorenzo König, Maxwell Millar-Blanchaer, Olivier Absil, Dimitri Mawet, Niyati Desai, Daniel Echeverri, James K. Wallace, Jon Schuller, and Demis John

Motivation

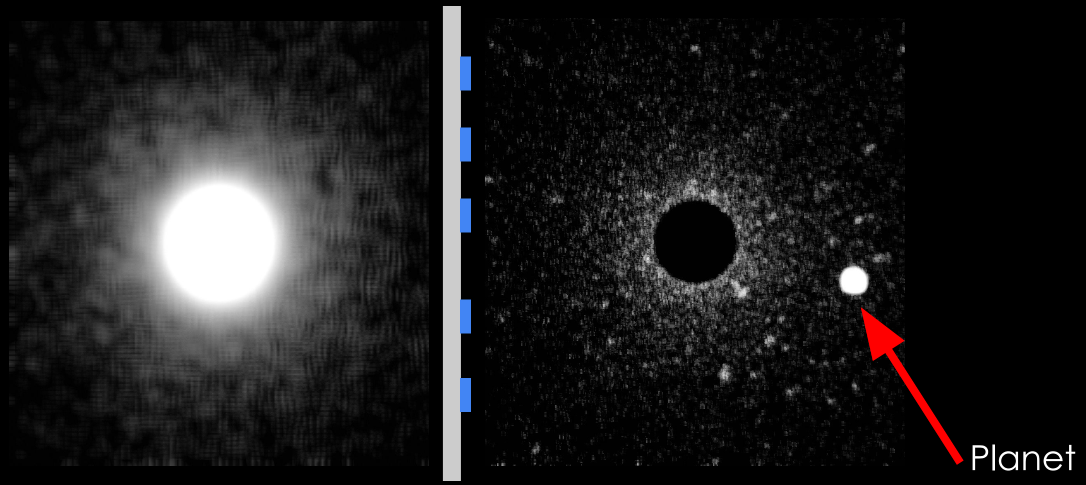
- To reach earth-like (10^{-10}) contrasts, direct imaging systems need improvement

- 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)

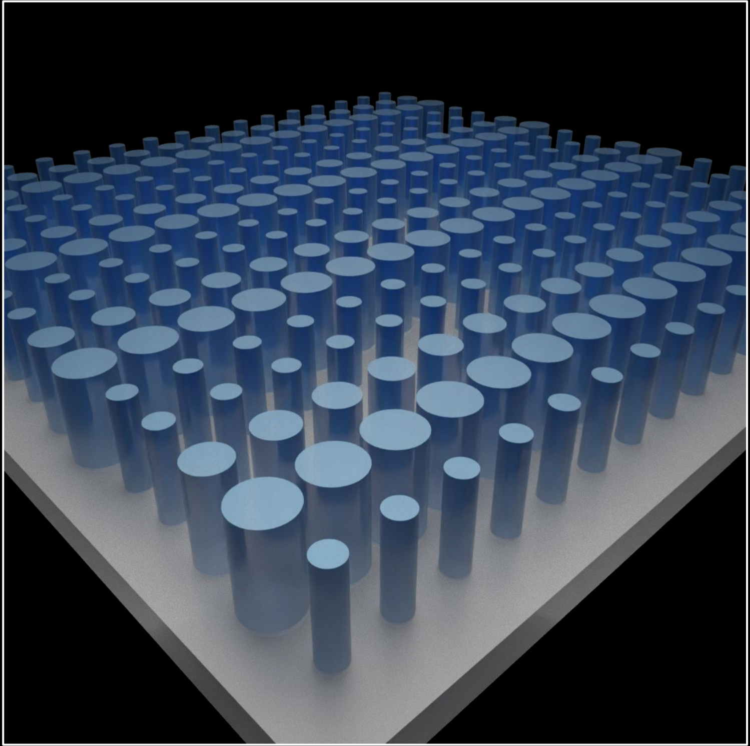
- With metasurfaces, we can design achromatic SVCs and multiplexed VVCs

Metasurface Coronagraph



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.

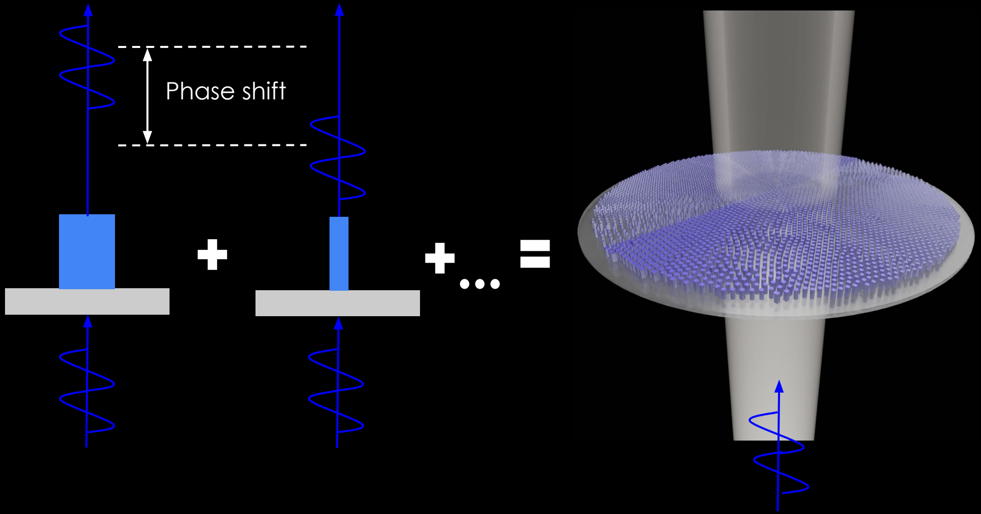


How do metasurfaces work?

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

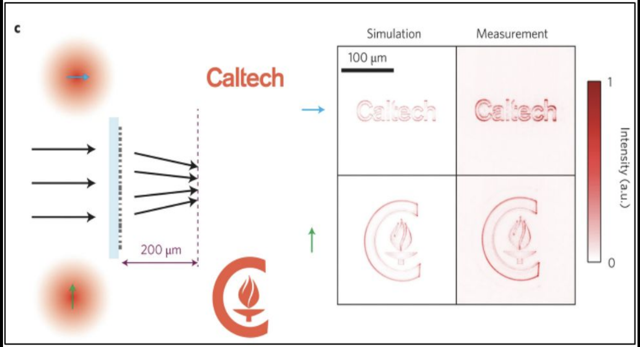
- Unit cell: nanostructure + patch of substrate

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



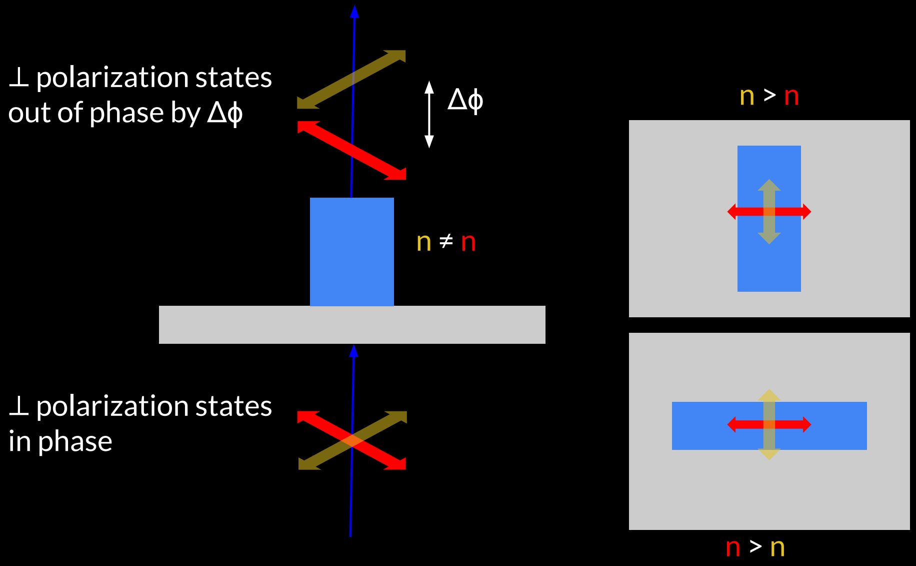
Relevant review papers: Kamali et al. 2018, Neshev and Aharonovich 2018, Lee et al. 2020, Hu et al. 2021

How do metasurfaces work?



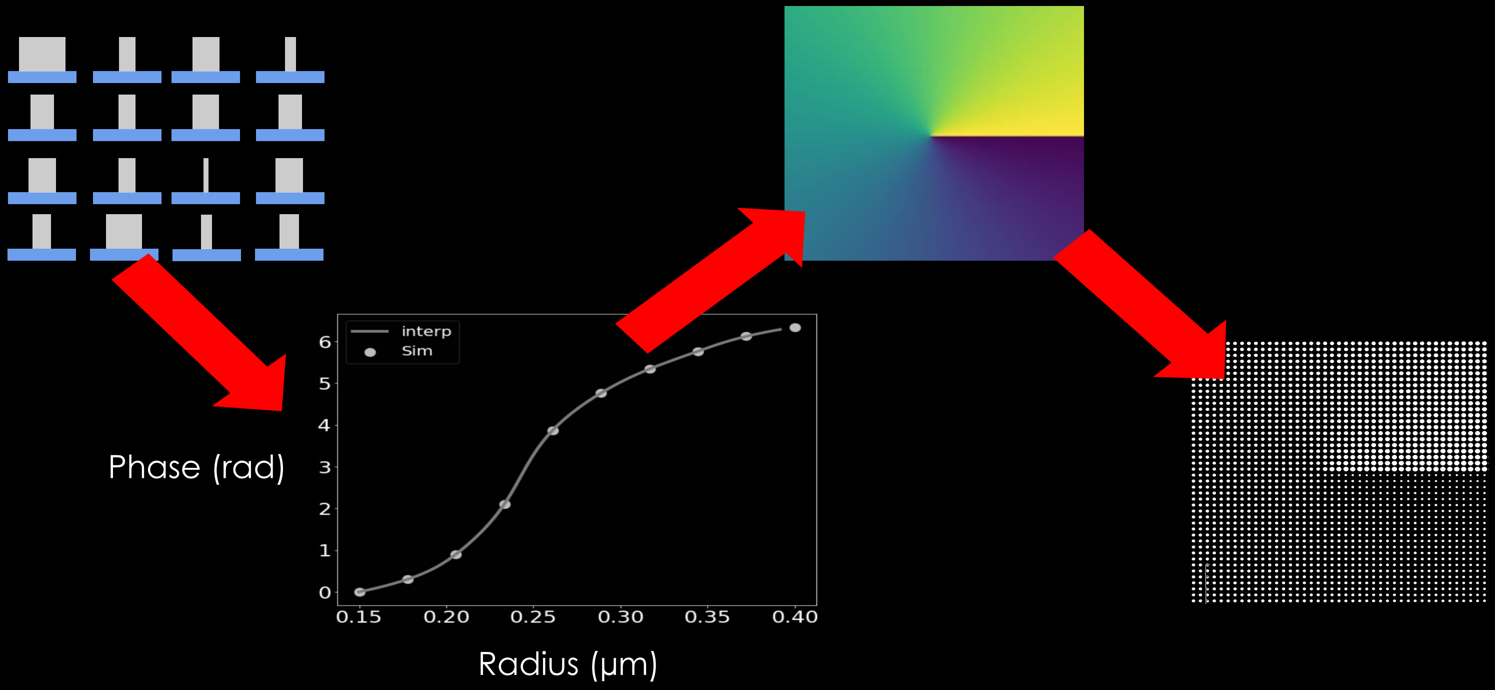
Arbabi et al 2015

- **Polarization sensitive:** changing shape side lengths/spacing at fixed height changes n_{eff} differently for ⊥ polarizations
- Unit cell: 
- Optical behavior can be different for ⊥ polarizations



How do you design a metasurface?

Simplest way: forward design



How do you design a metasurface?

My method: fast, robust optimization built off of forward design

FDTD SWEEP → **OPTIMIZE CLOCKING** → **NANOSTRUCTURE SELECTION** → **PROFILE MAPPING**

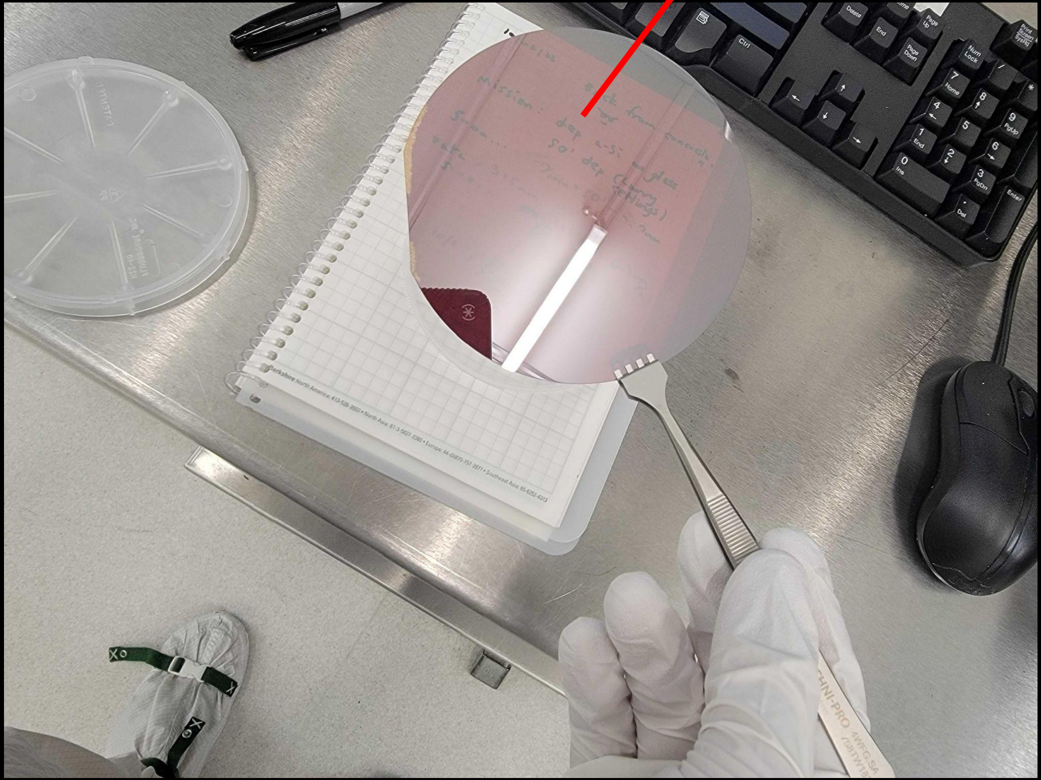
How do you design a metasurface?

a-Si on glass

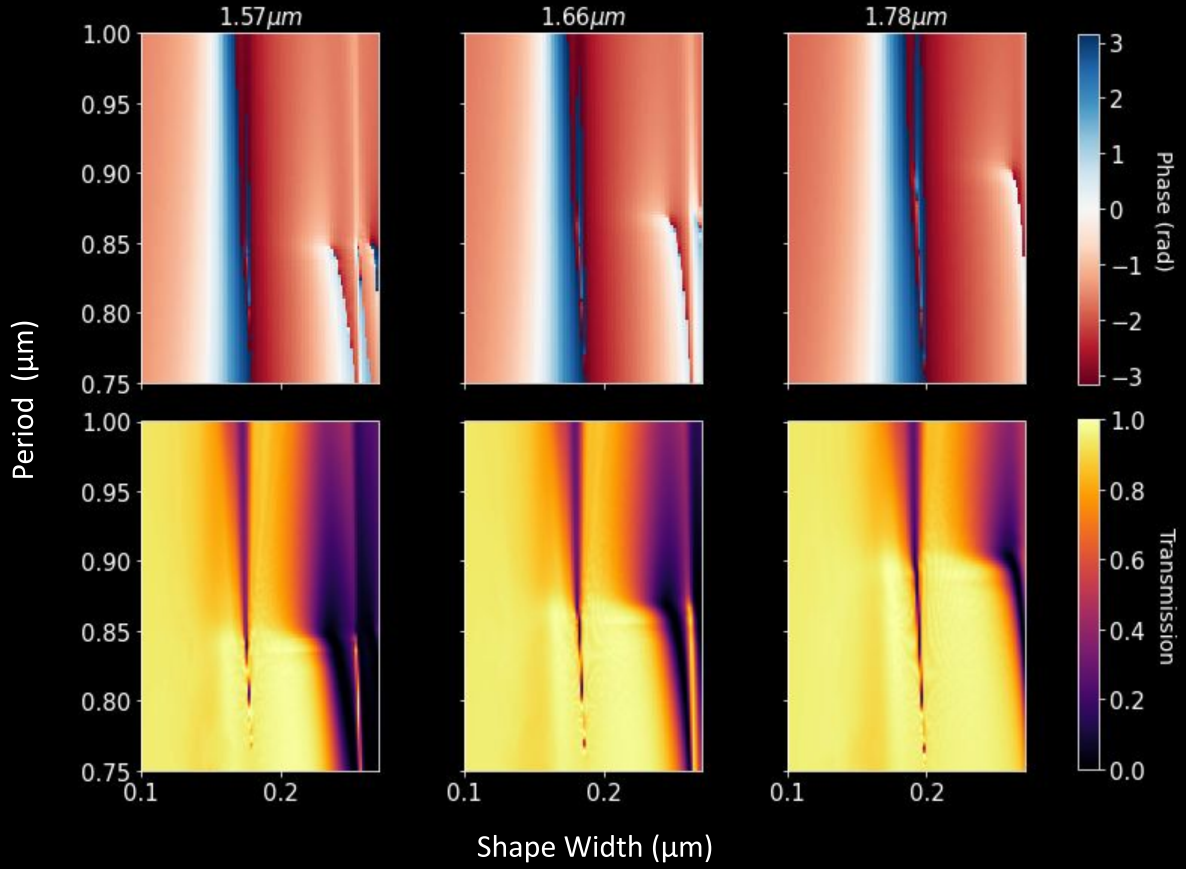
Preliminary Considerations:

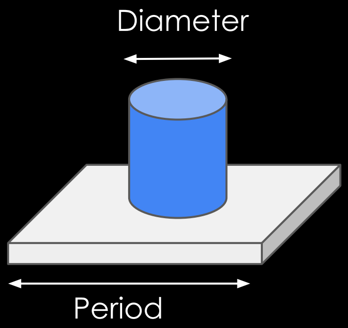
- Materials

- Fabrication constraints

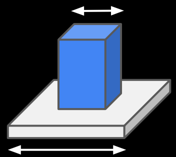


Metasurface Optimization: FDTD Sweep

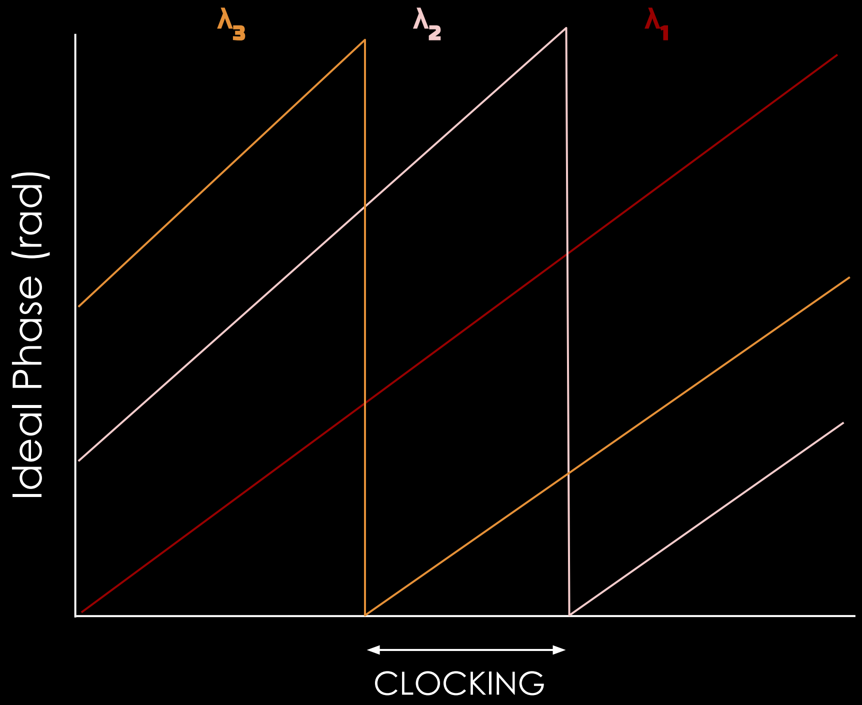


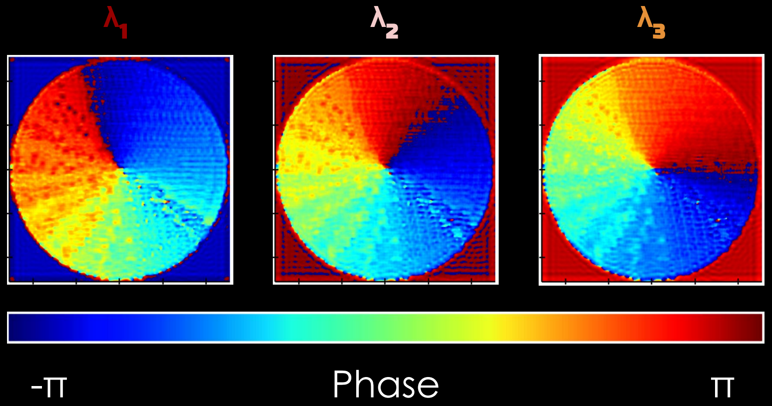


Also sweep other shapes

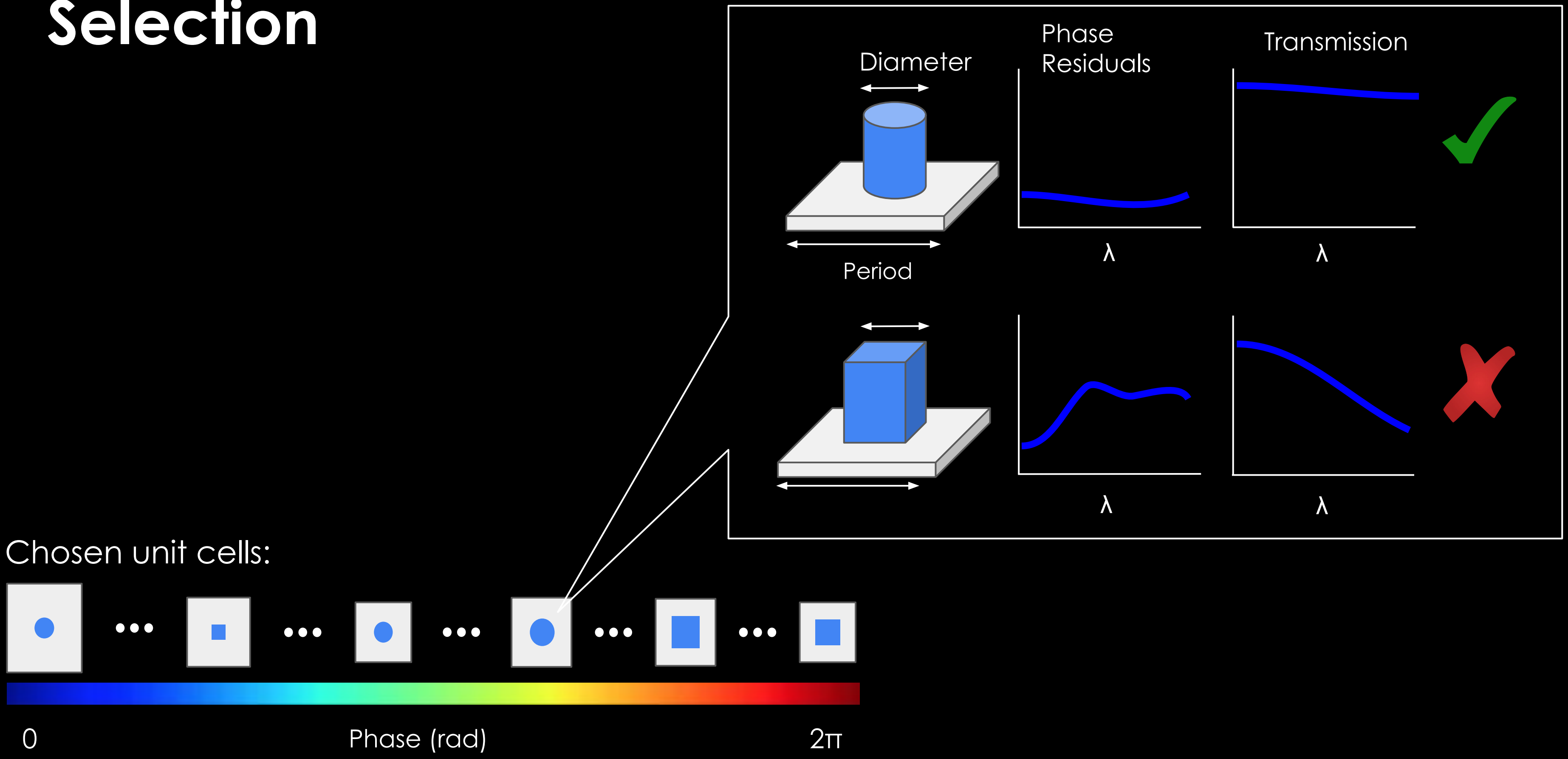


Metasurface Optimization: Clocking Optimization

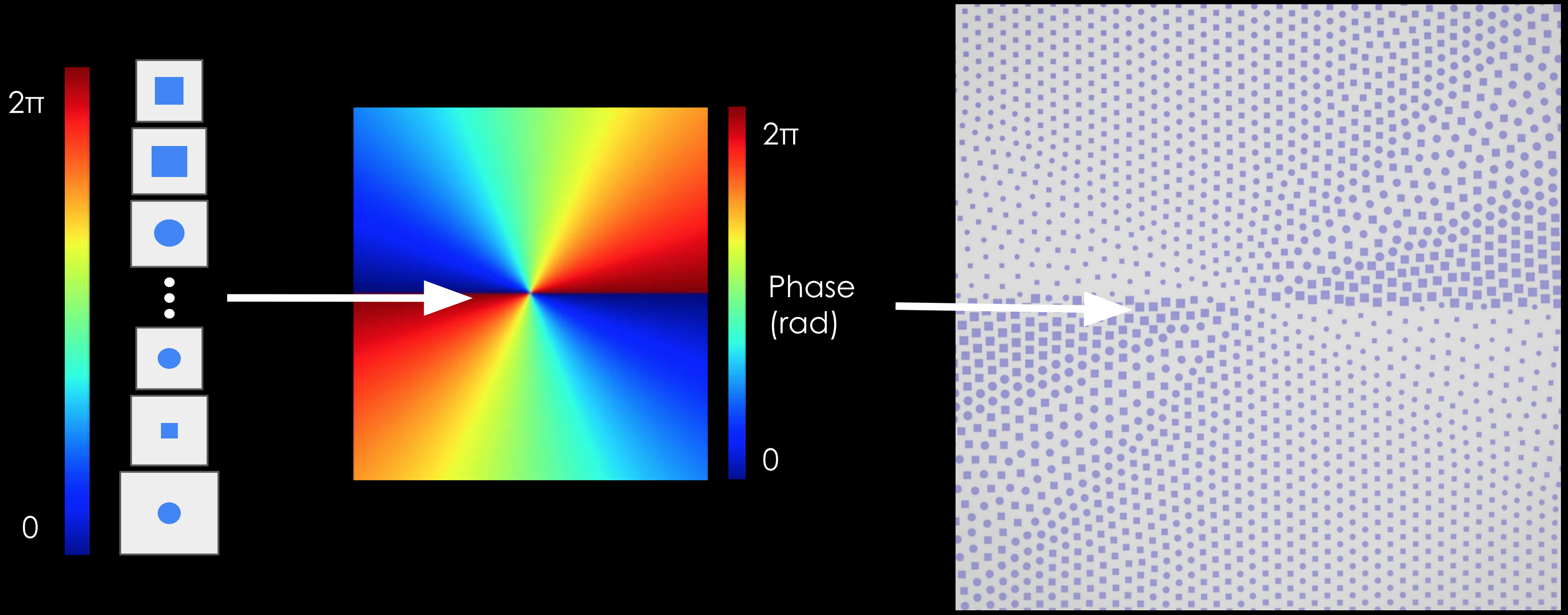




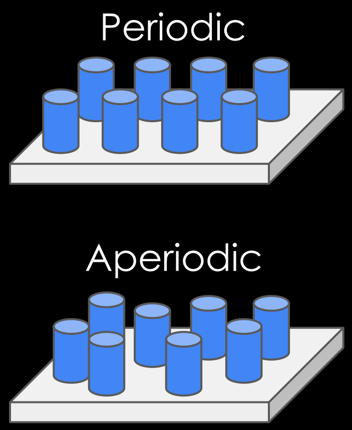
Metasurface Optimization: Nanostructure Selection



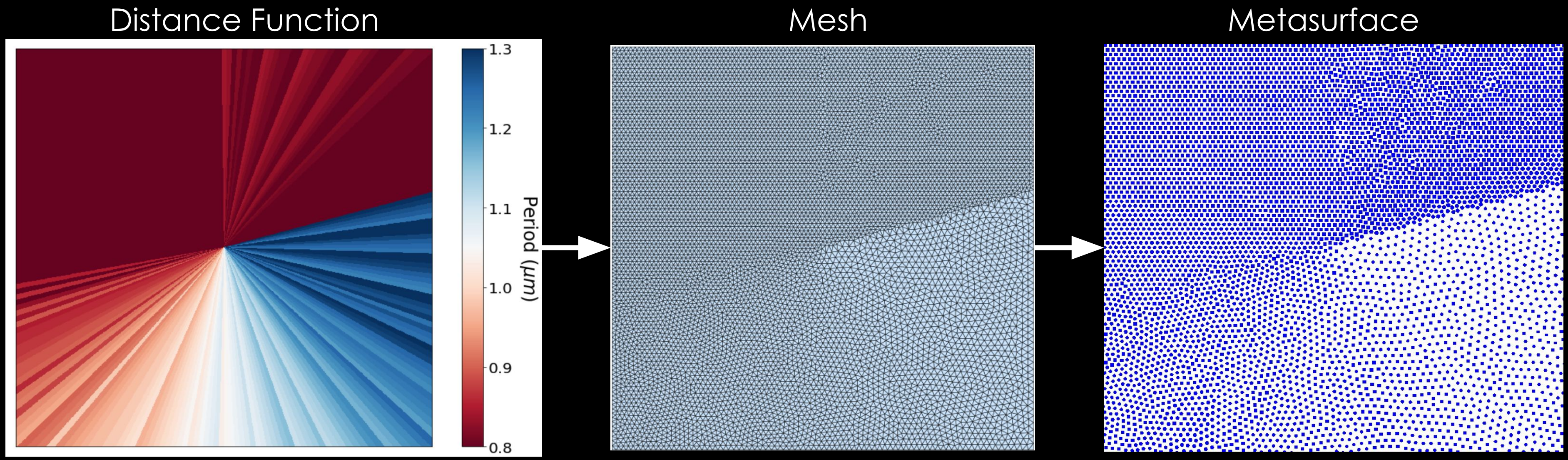
Metasurface Optimization: Profile Mapping



Metasurface Optimization: Aperiodicity

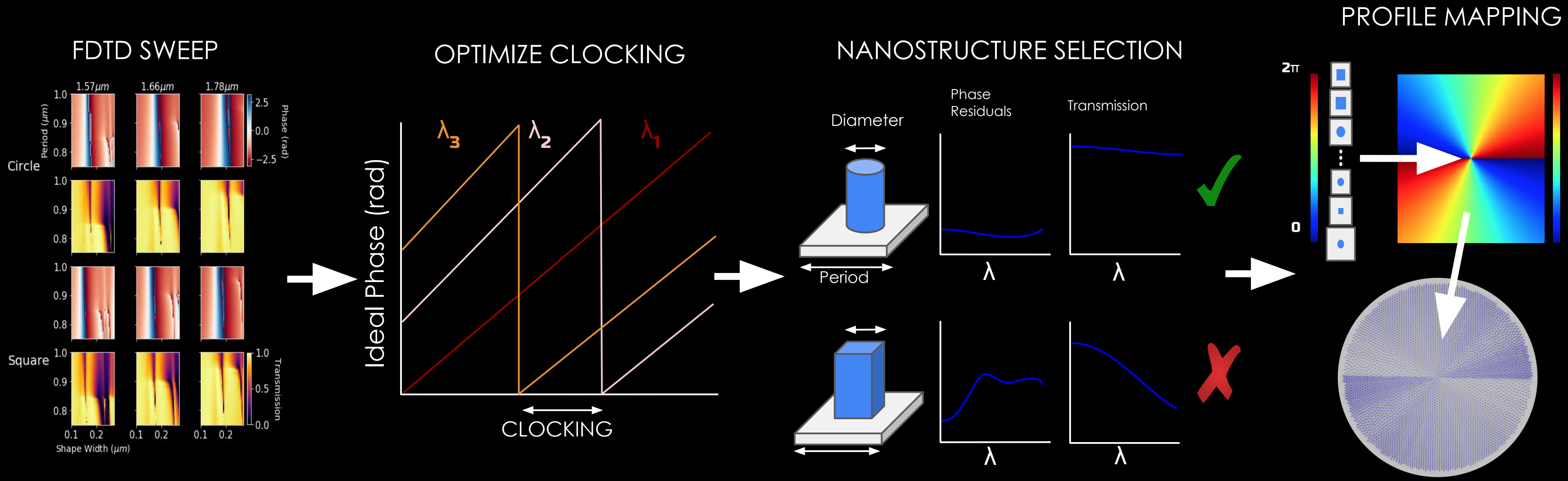


- Arbitrary aperiodic metasurfaces have never been demonstrated to our knowledge
- We show that this technique can be used for achromatization of metasurfaces (paper coming soon!)
- Unit cells arranged using meshing software DistMesh (Persson et al. 2004)



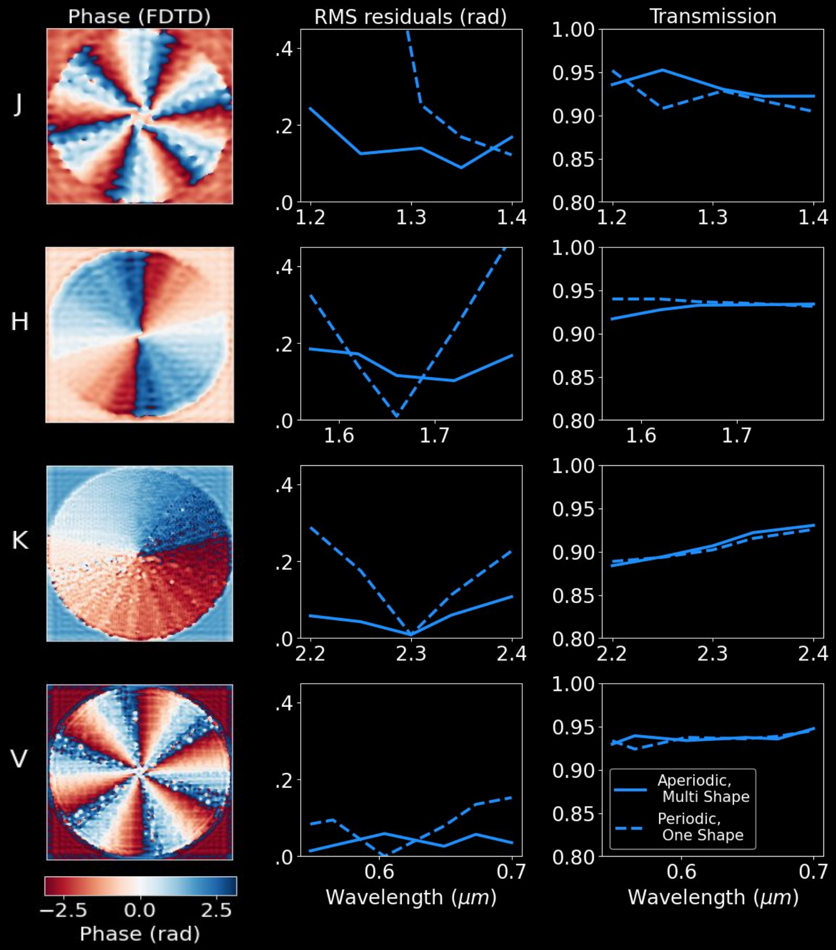
How do you design a metasurface?

My method: fast, robust optimization that works better than forward design

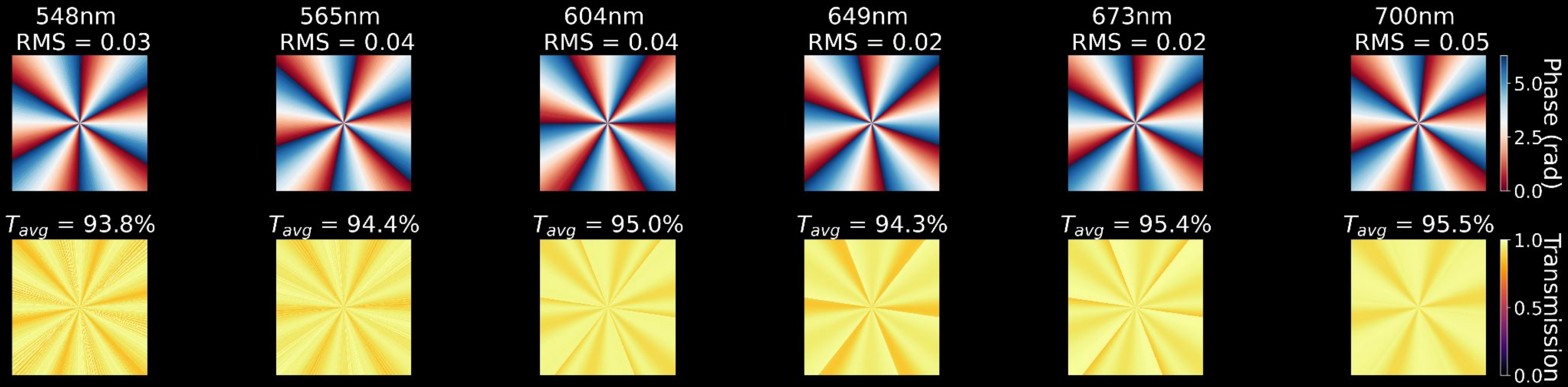


Optimized metasurface (simulated) performance

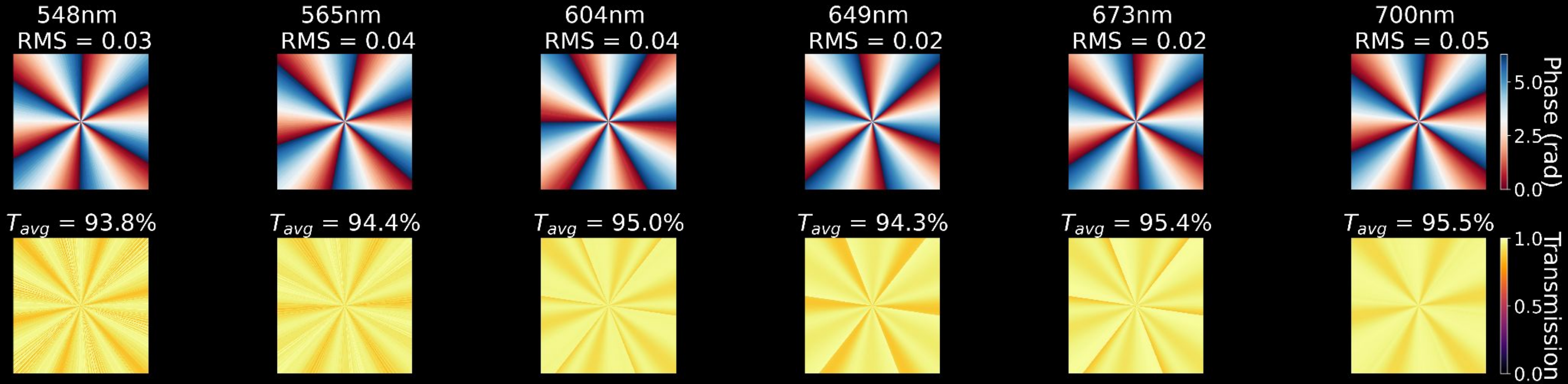
- We design J, H, K, and V metasurface scalar vortices (MSVs) operating over 15-20% bandwidth
- J, H, and K designs have features compatible with photolithography

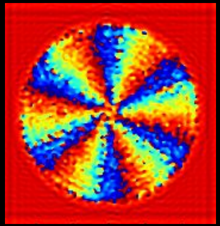


V-band charge-6 metasurface (simulated) performance



V-band charge-6 metasurface (simulated) performance



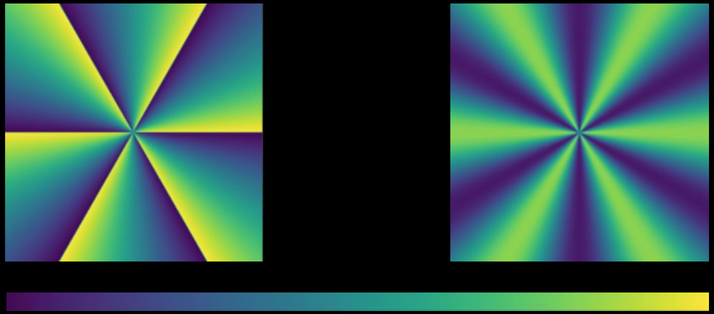


Optimized metasurface (simulated) performance

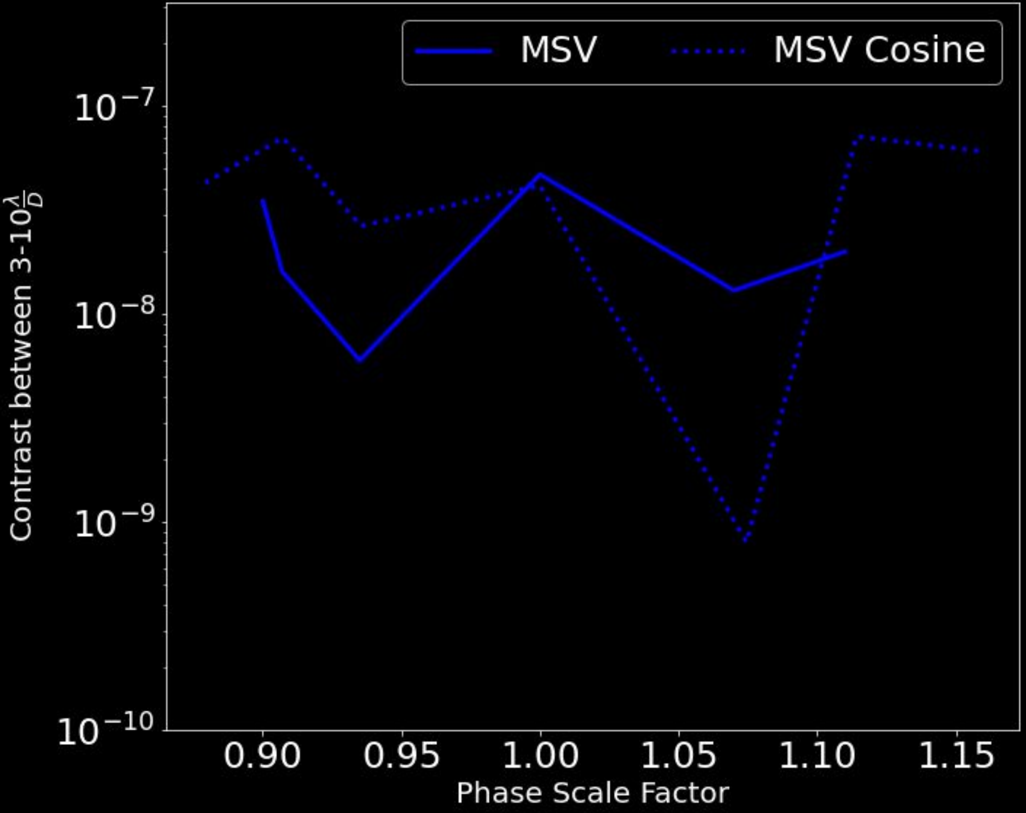
Contrast

Try two metasurface scalar vortex designs:

conventional charge 6 | cosine charge 6 (Ruane et al. 2019)



0 … 2π

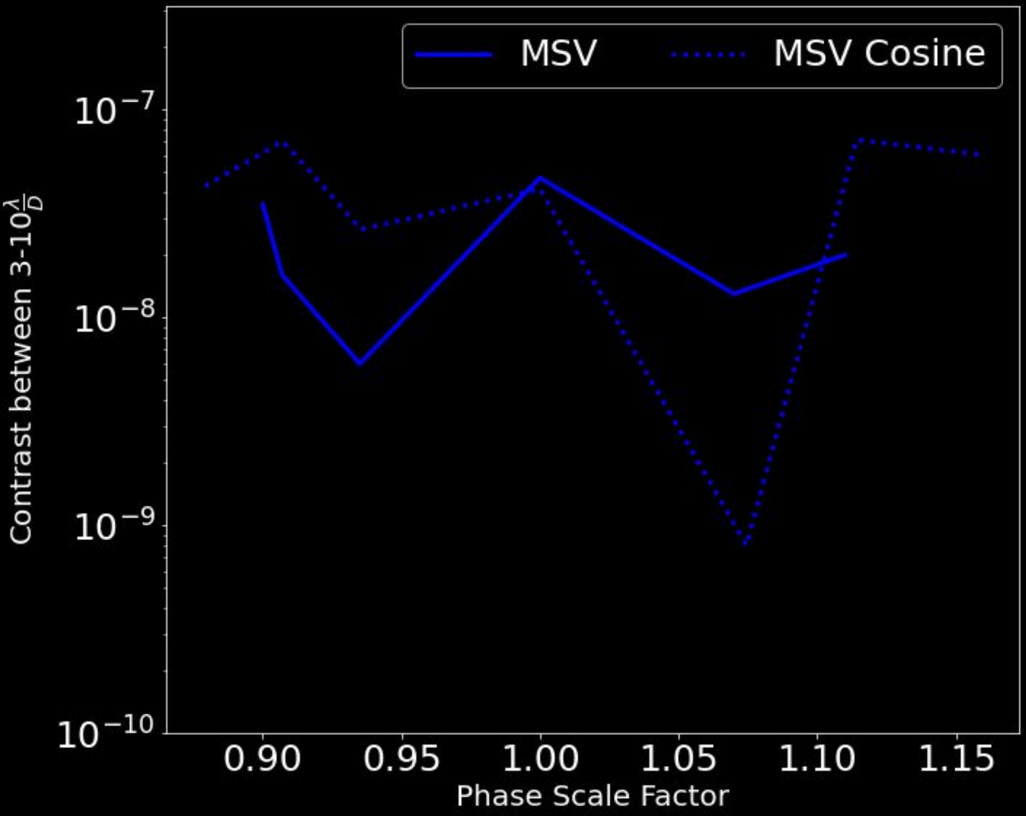


Optimized metasurface (simulated) performance

Contrast

Using multiple nanostructure shapes and variable spacing, we improve achromatic performance compared to conventional SV's

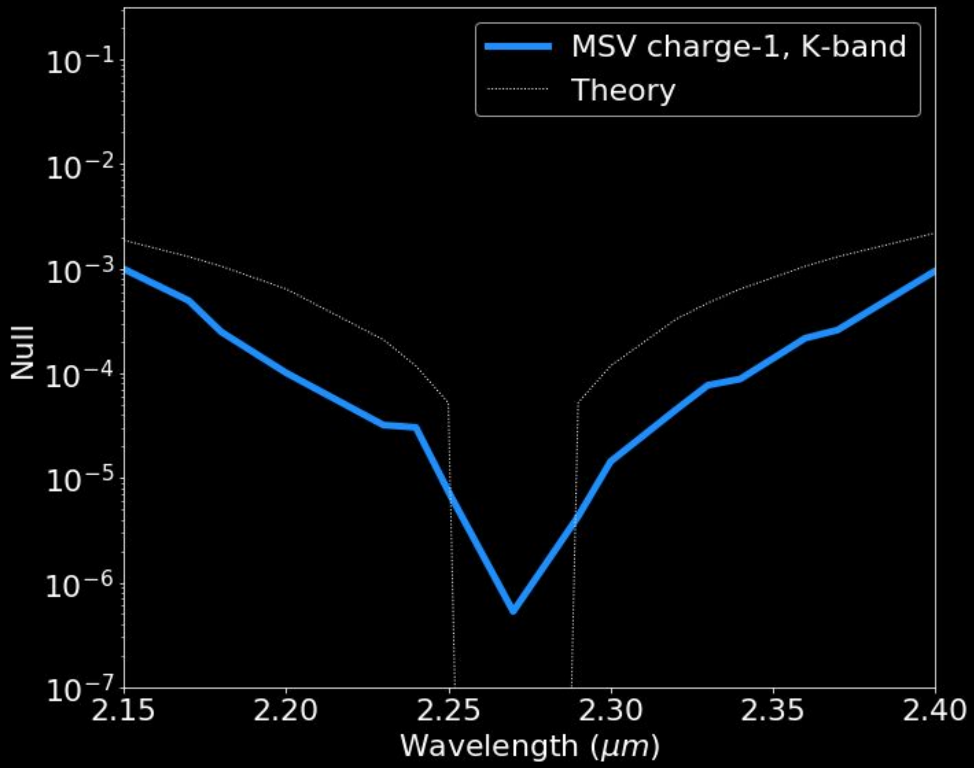
We expect to get deeper contrasts as we expand our unit cell shape library and/or use a multi-layer platform



Optimized metasurface (simulated) performance

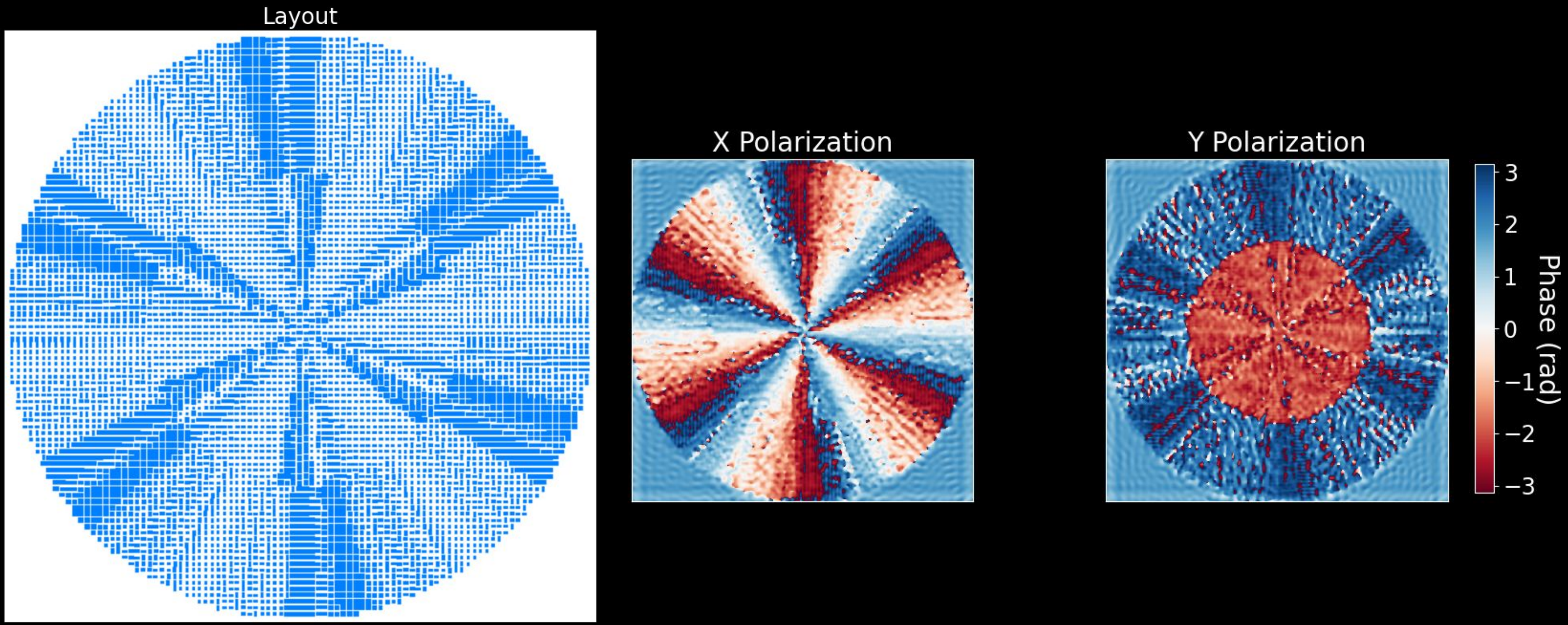
Vortex Fiber Nulling

Our simulated K-band charge-1 vortex beats theoretical null depth



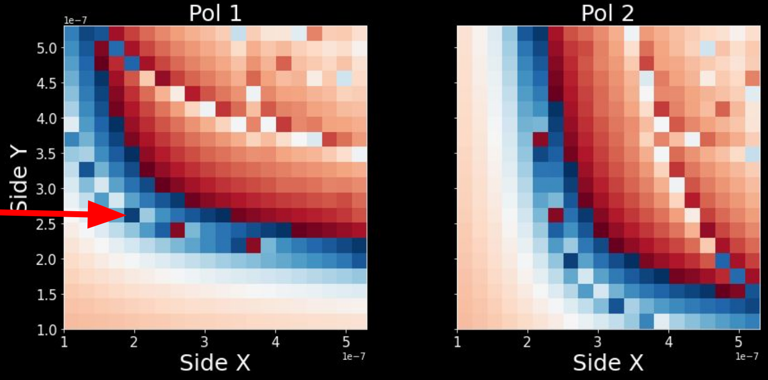
Optimizing a Polarized metasurface

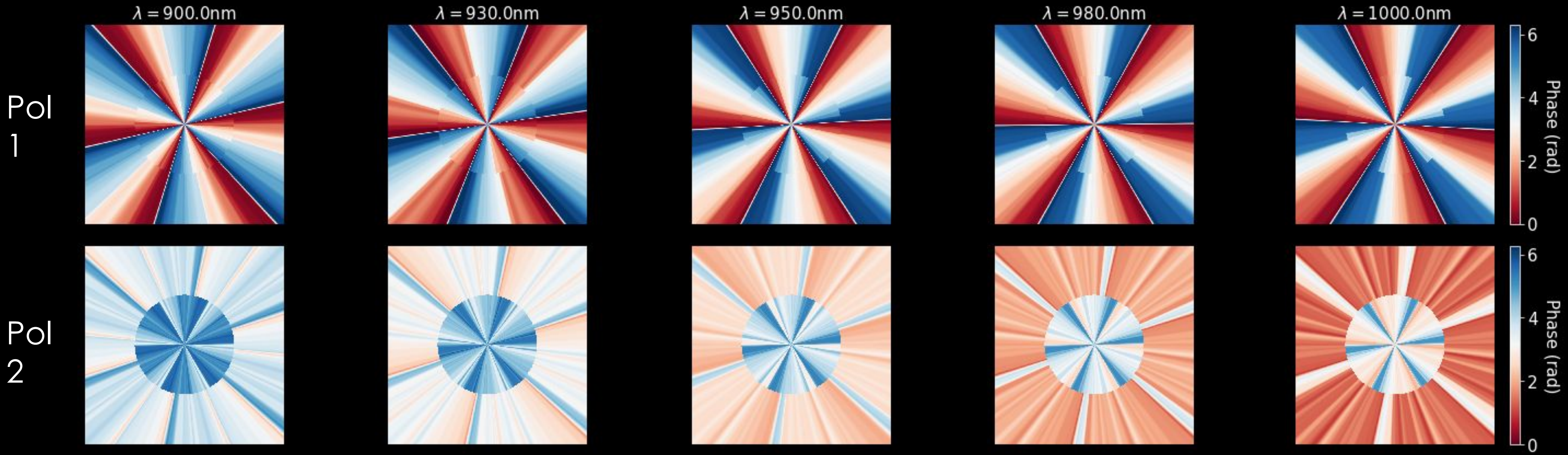
- I have added polarization dependent functionality to my optimization - here's some preliminary H-band results!



Achromatizing a Polarized metasurface

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

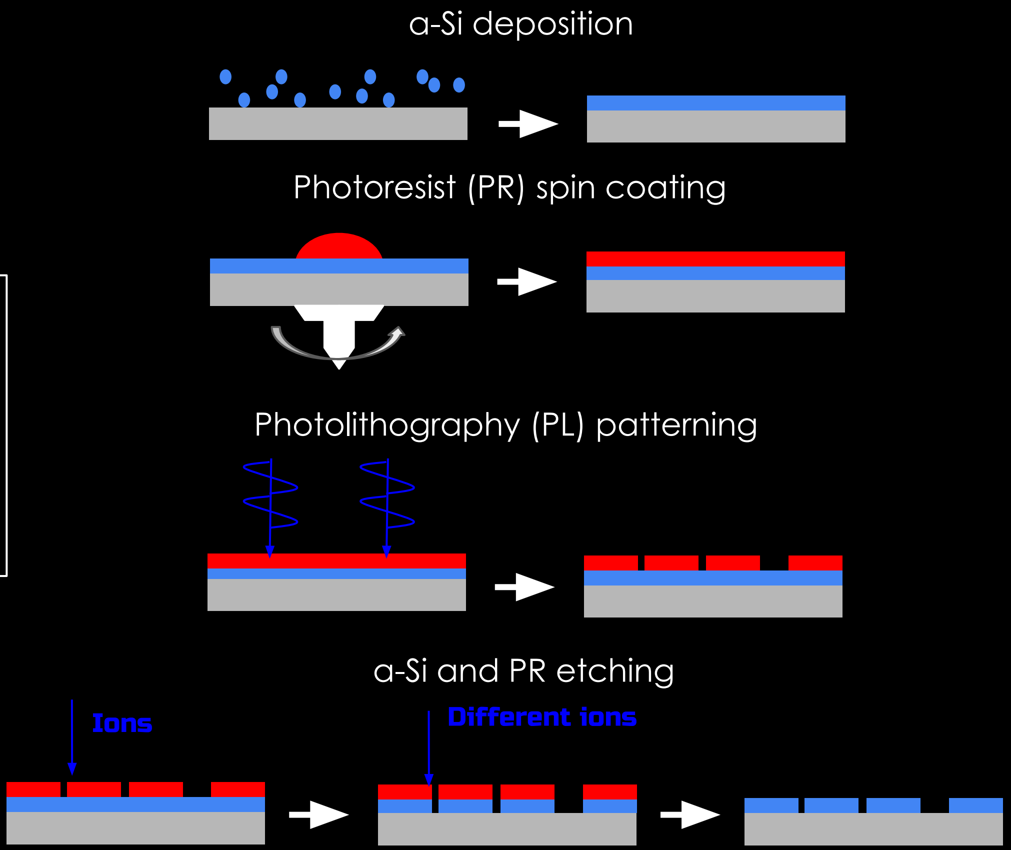




Metasurface Fabrication

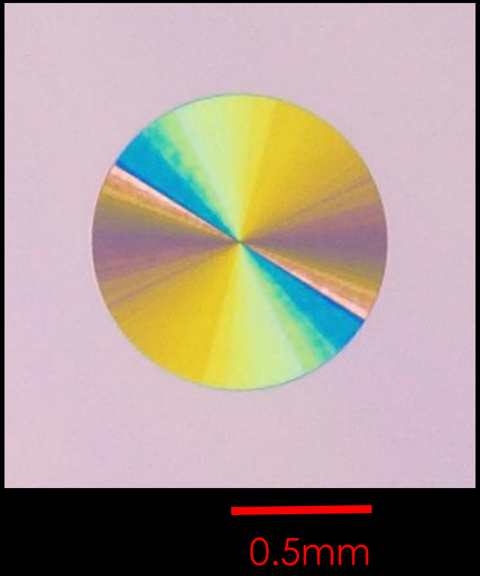
We (so far) use a photolithography based platform with a-Si structures on SiO_2 substrate

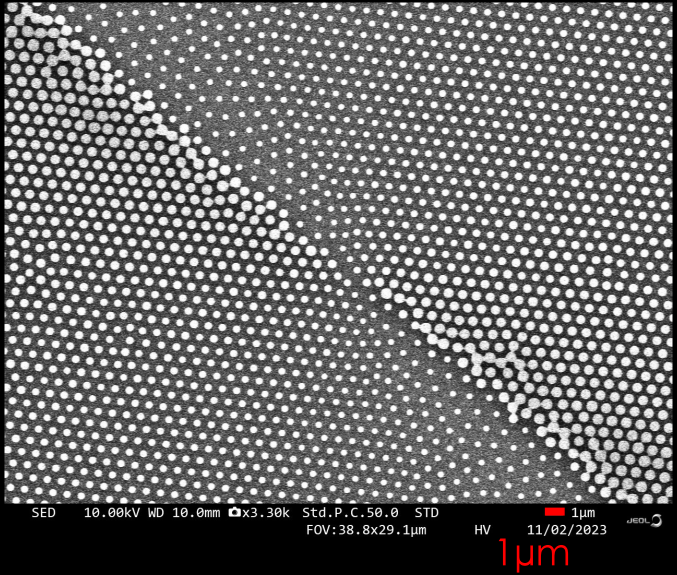
An electron-beam lithography (EBL) process would be very similar!

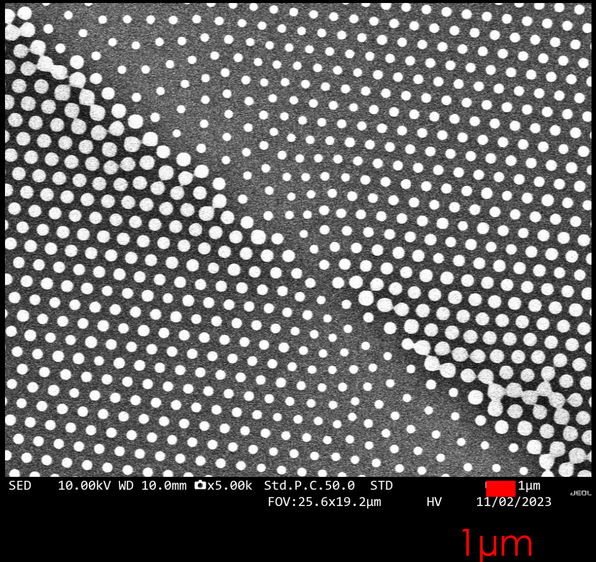


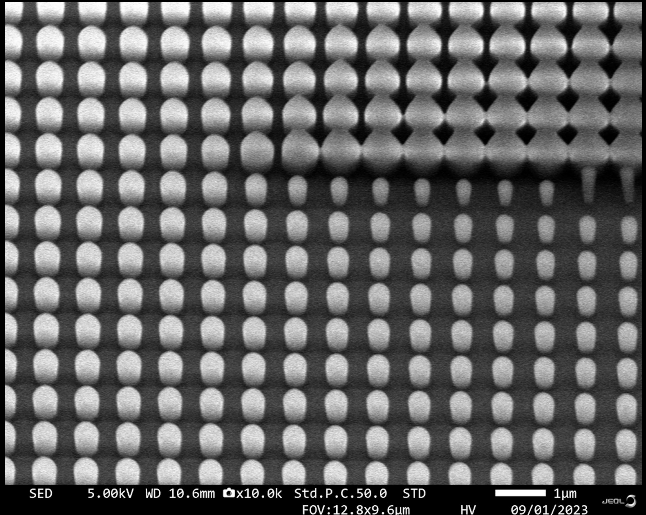
Preliminary Fabrication Results

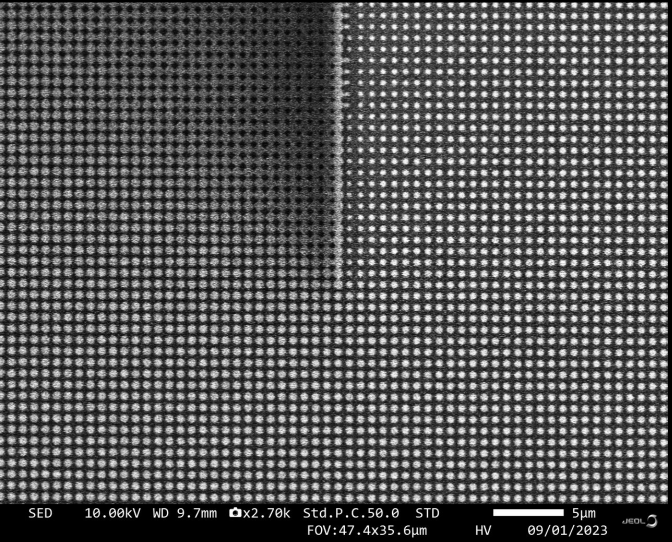
- As we perfect our achromatic designs, we have begun refining our fabrication process with simple, one-shape metasurface vortices

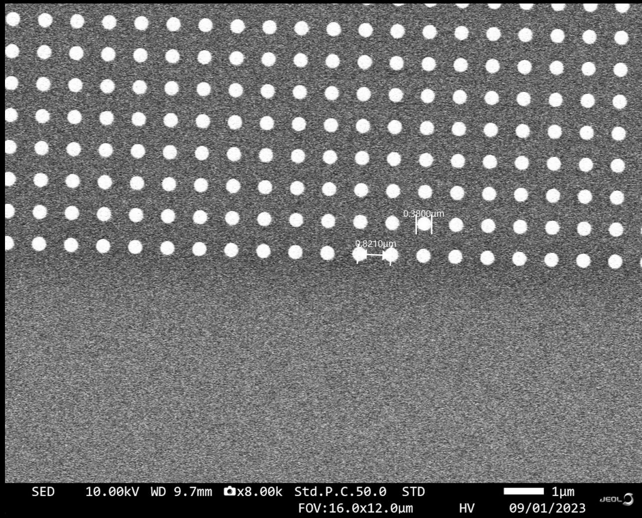






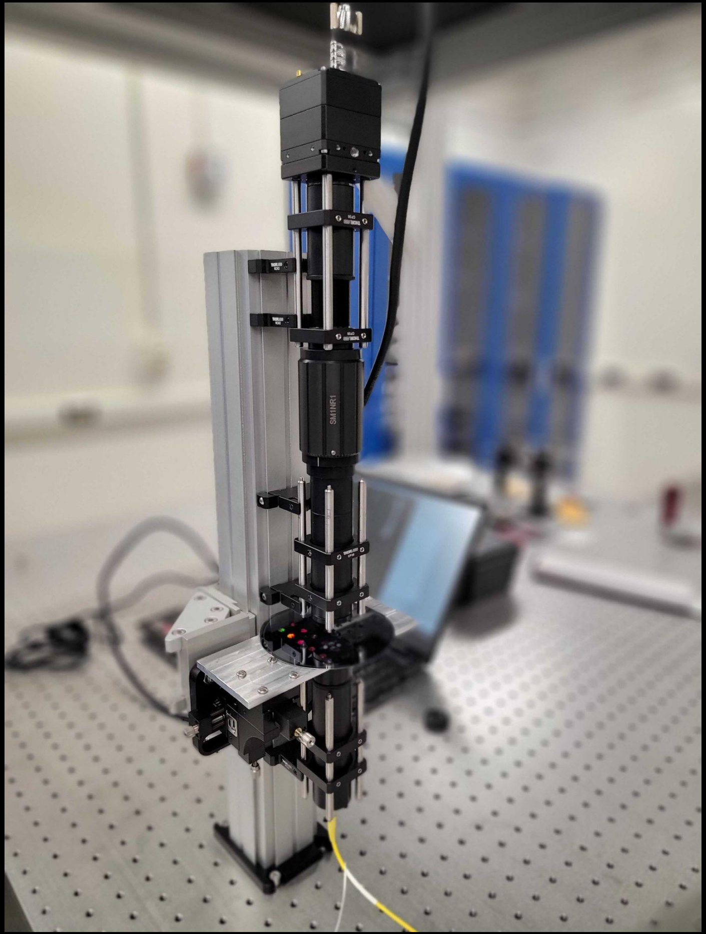

SED 5.00kV WD 10.6mm x10.0k Std.P.C.50.0 STD 1µm
FOV:12.8x9.6µm HV 09/01/2023


SED 10.00kV WD 9.7mm x2.70k Std.P.C.50.0 STD 5µm
FOV:47.4x35.6µm HV 09/01/2023

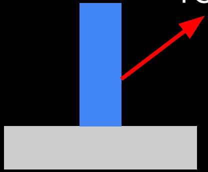

0.3800µm
0.8210µm
SED 10.00kV WD 9.7mm x8.00k Std.P.C.50.0 STD 1µm
FOV:16.0x12.0µm HV 09/01/2023

Metasurface characterization

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



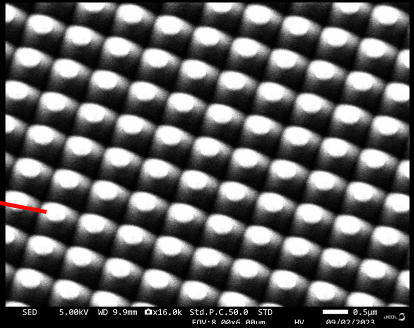
Preliminary Characterization Results



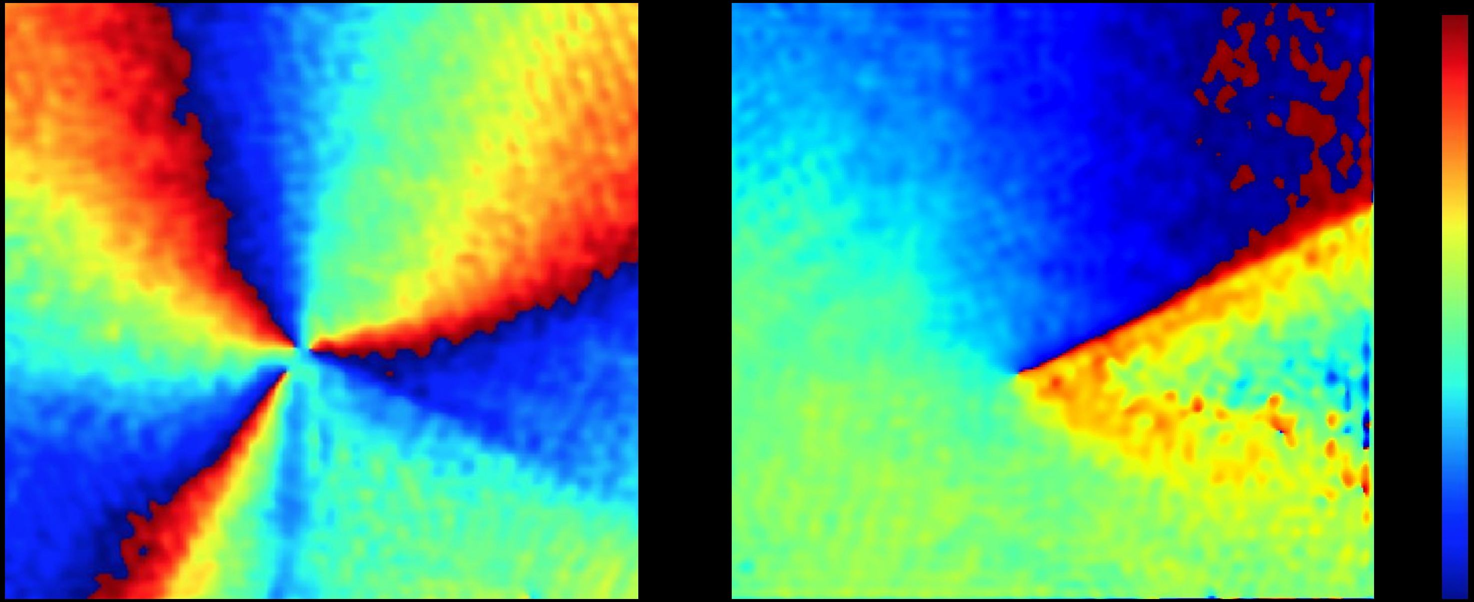
Too tall!

Very over-etched sample

Too wide!

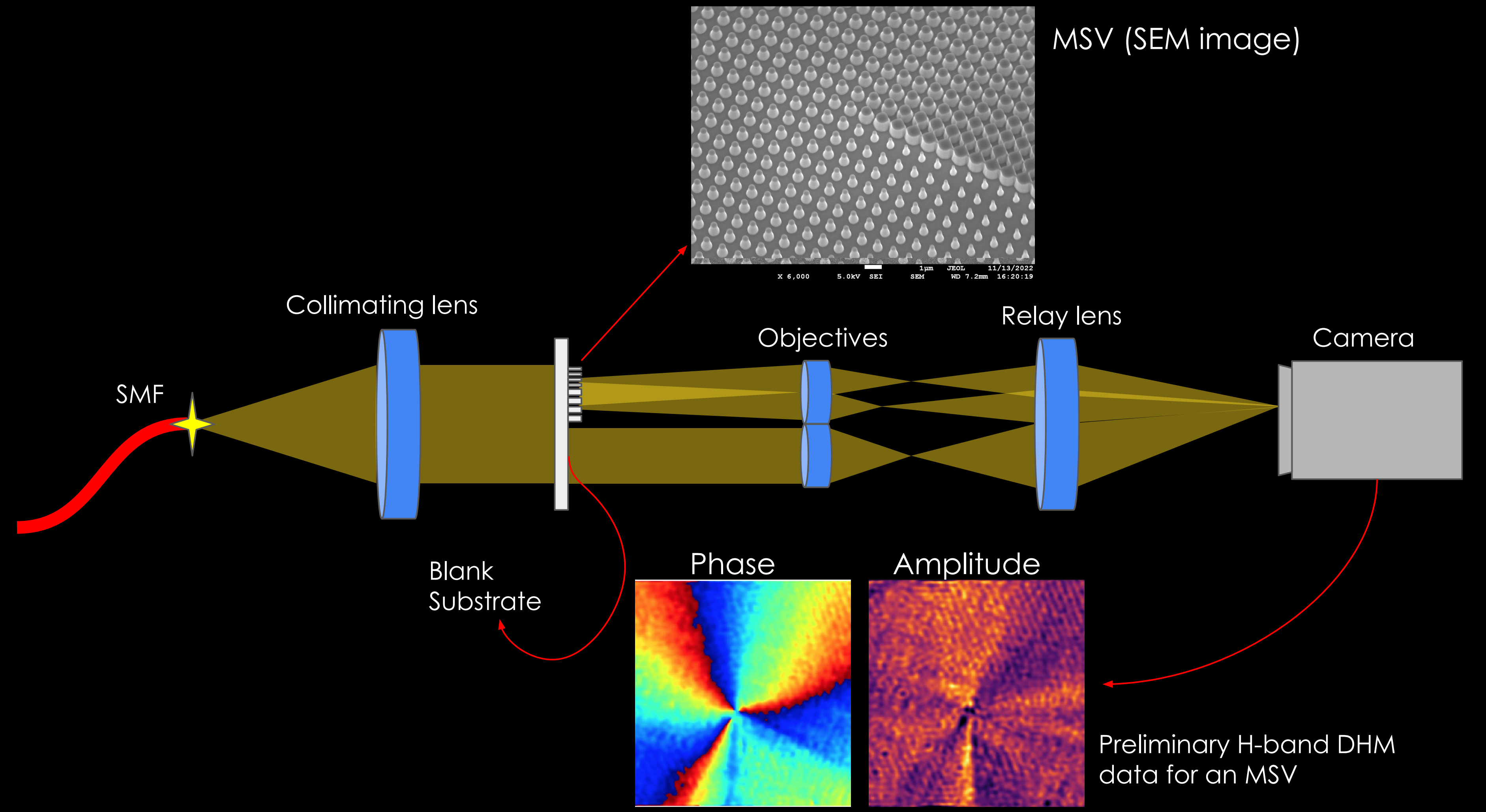


Poorly-etched sample



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


MSV (SEM image)
1µm JEOL 11/13/2022
X 6,000 5.0kV SEI SEM WD 7.2mm 16:20:19
Collimating lens
SMF
Objectives
Relay lens
Camera
Blank
Substrate
Phase
Amplitude
Preliminary H-band DHM
data for an MSV