National Aeronautics and Space Administration

Metasurface Optics for Zernike Wavefront Sensing

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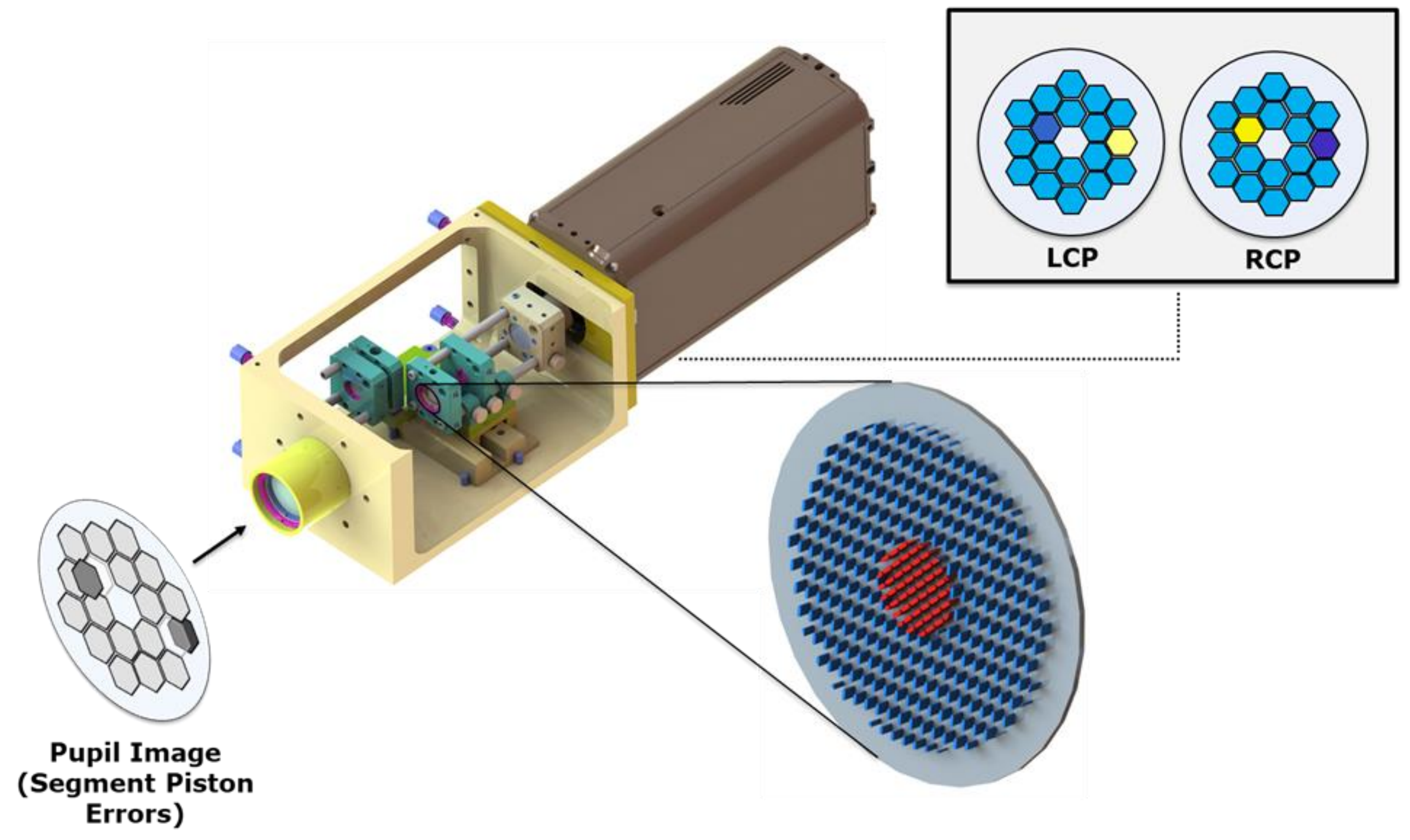
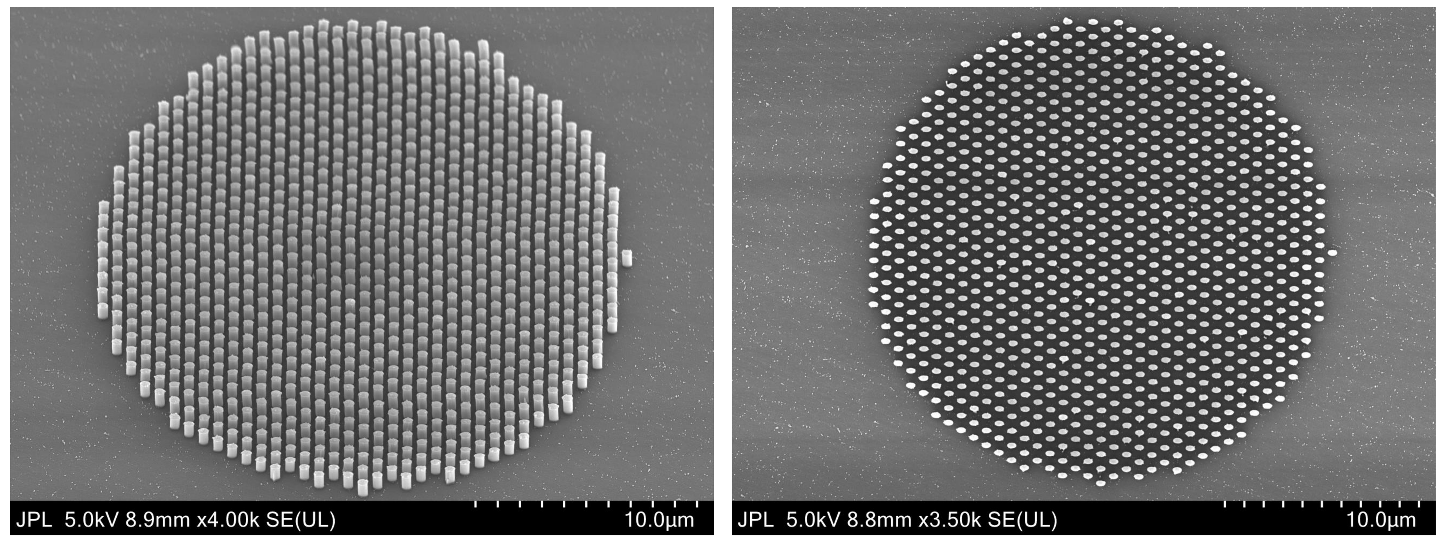
Program: FY21 R&TD Topics **Strategic Focus Area: Advanced Optics Systems and Telescopes**

Objective: Develop and demonstrate the use of metasurface optics to achieve photon-efficient, high precision wavefront sensing for future astronomy missions.

Background: Direct detection of exoplanets via coronagraphic imaging is a priority for NASA. However, there are many challenges associated with this goal including measuring and maintaining wavefront errors at the picometer level for extended periods of time. The Zernike Wavefront Sensor (ZWFS) has the sensitivity to accurately measure errors at these levels, however it has limitations related to the magnitude of phase errors that it can detect, and the spectral bandpass over which it can operate. In this effort, we overcome these challenges by implementing a "vector" form of the ZWFS, which provides two unique wavefront-sensing signals depending on the polarization state of the incoming light. We achieve this through metasurface optics – arrangements of subwavelength features that modulate optical parameters depending on the shape, size, and relative orientation of these features, as well as the materials used to construct them. Using metasurfaces, the dynamic range of the measurement can be increased by a factor of 4x allowing for larger phase aberrations to be characterized. Furthermore, the device can be designed to operate over a large spectral band providing a highly photon-efficient wavefront sensing technique of relevance for future space missions such as HabEx or LUVOIR.



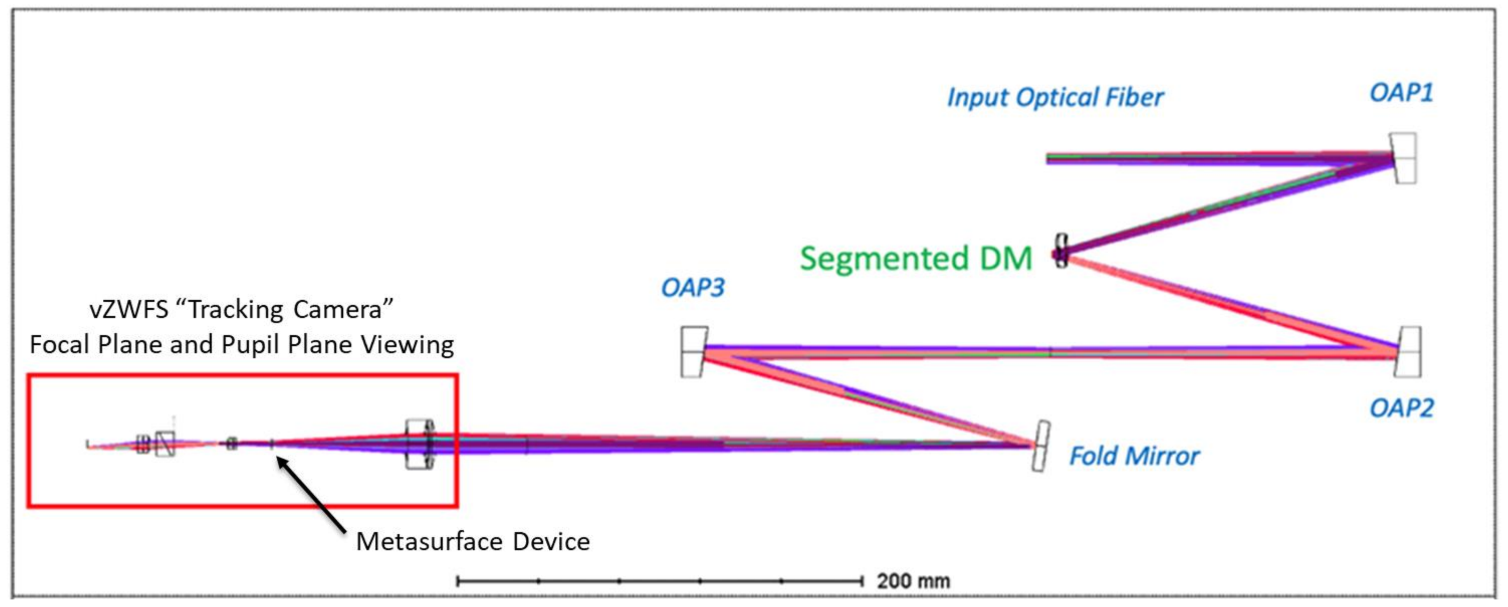
Overview of metasurface wavefront sensor concept. Two unique intensity images corresponding to the Left/Right Circular Polarized (LCP/RCP) light are produced on the sensor. The signal from the two patterns can be used to reconstruct the phase of the incoming wavefront using iterative algorithms.

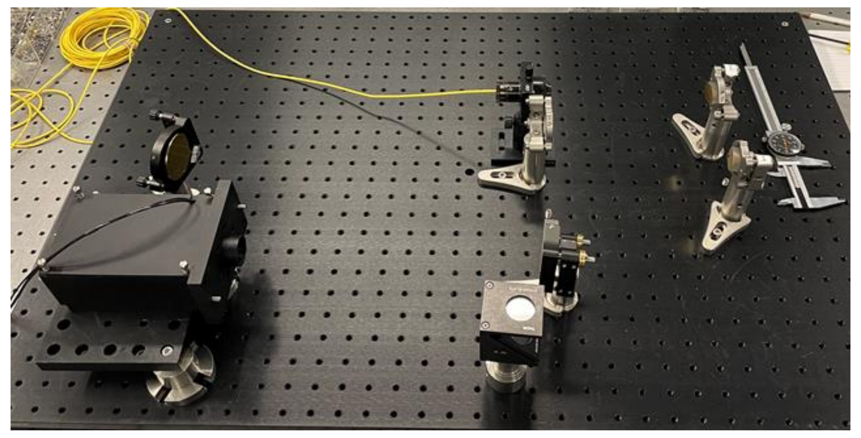


SEM images of a fabricated metasurface device seen at a view angle of 30° (left) and directly from above (right). The metasurface region shown in the images have a diameter of 23.8 µm and consists of elliptical nanopillars 900 nm tall made of amorphous silicon on a glass substrate.

Progress / Milestones

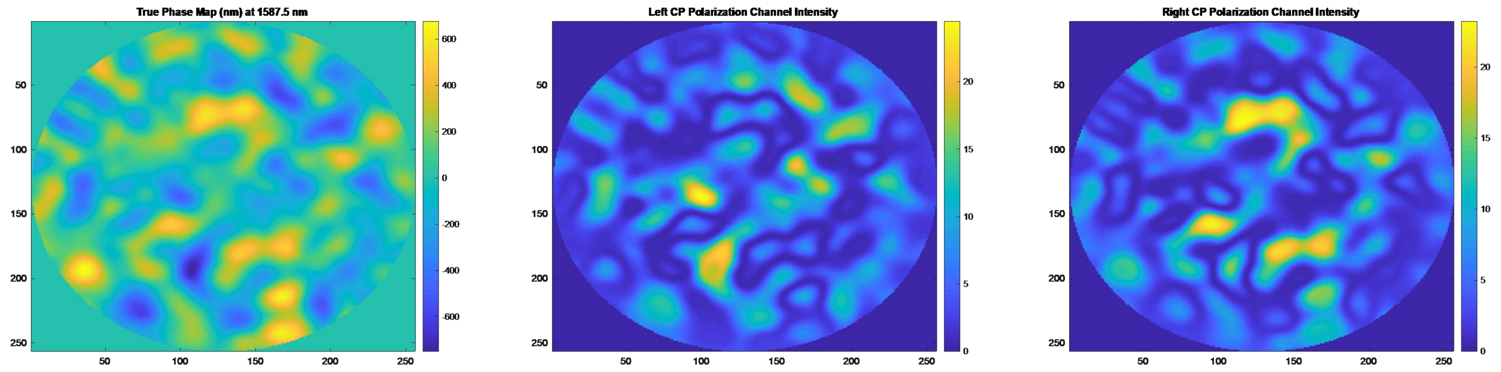
- Fabrication of metasurface device in JPL's Microdevices Laboratory (MDL)
- Testbed established in building 299, hardware is compatible with future Keck Planet Imager and Characterizer (KPIC) demo
- Iterative numerical algorithms developed for phase reconstruction
- Preliminary on-sky data acquired using scalar ZWFS dimple

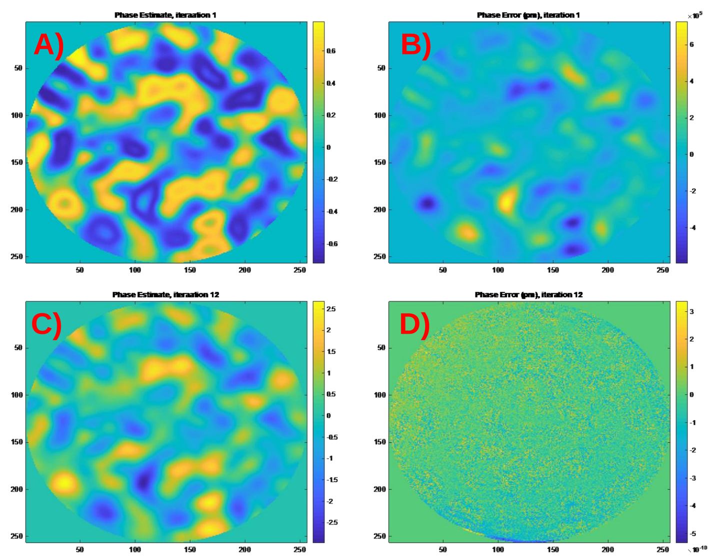




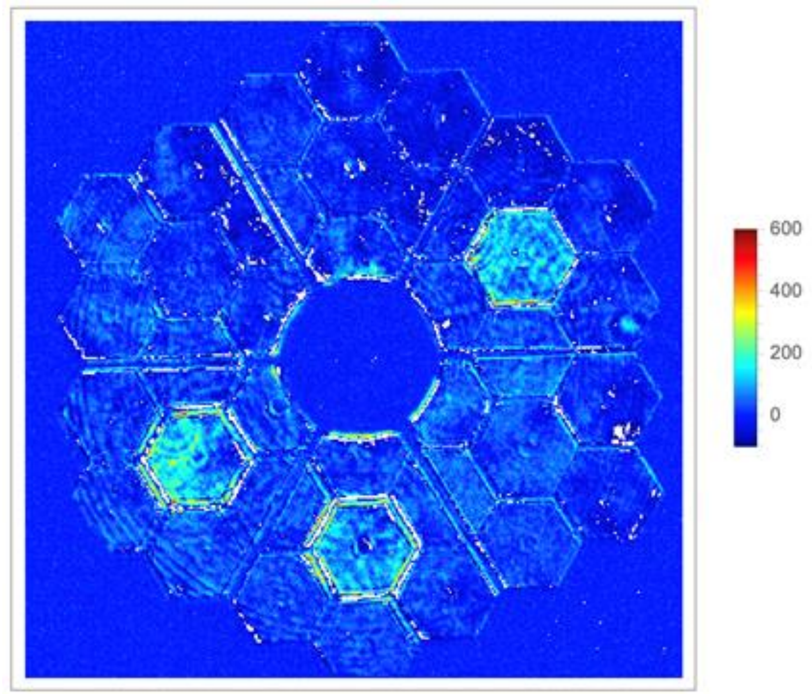
(Top) Optical layout of the metasurface testbed. Light enters the system from the fiber at the top, is collimated at the location of the segmented DM, magnified by the combination of OAP2 and OAP3 to generate a pupil at the fold mirror. (Left) Picture of the optical testbed in building 299.

vZWFS Reconstruction Example Results





Top Row: (Left) True phase map, with 750 nm peak amplitude at 1587 nm, (Middle) Left Polarization Channel Bandpass integrated Intensity, and (Right) Right Polarization Channel Bandpass Intensity
(A) First iteration wavefront estimate, and **(B)** error in picometers, with a rms of 130 nm. **(C)** Phase map after 12 iterations, and **(D)** error map in picometers (machine precision)



On-sky data with the current (Phase I) implementation of the Keck Planet Imager and Characterizer (KPIC) instrument. Individual segments have been displaced producing "piston" errors which are readily sensed by the ZWFS.

Conclusions

- Vector-ZWFS technique can enable broadband, high dynamic range wavefront sensing for future astronomy missions
- Metasurface devices are space-environment compatible, and can be engineered for a wide range of imaging applications
- On-sky demonstration of metasurface ZWFS with KPIC to occur in FY22

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