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Vector Zernike WFS Progress at JPL: Liquid Crystal and Metasurface Devices and Applications

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Development of Vector Zernike WFS

- ZWFS Operational Principle
- Origin and development
- Applications
- ZWFS Limitations and next generation devices
- Vector Zernike with Liquid Crystal Devices
- Vector Zernike with Metasurface Devices
    - Metasurface Devices and Status
- Impact of ZWFS
- The Future

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Operational Principle

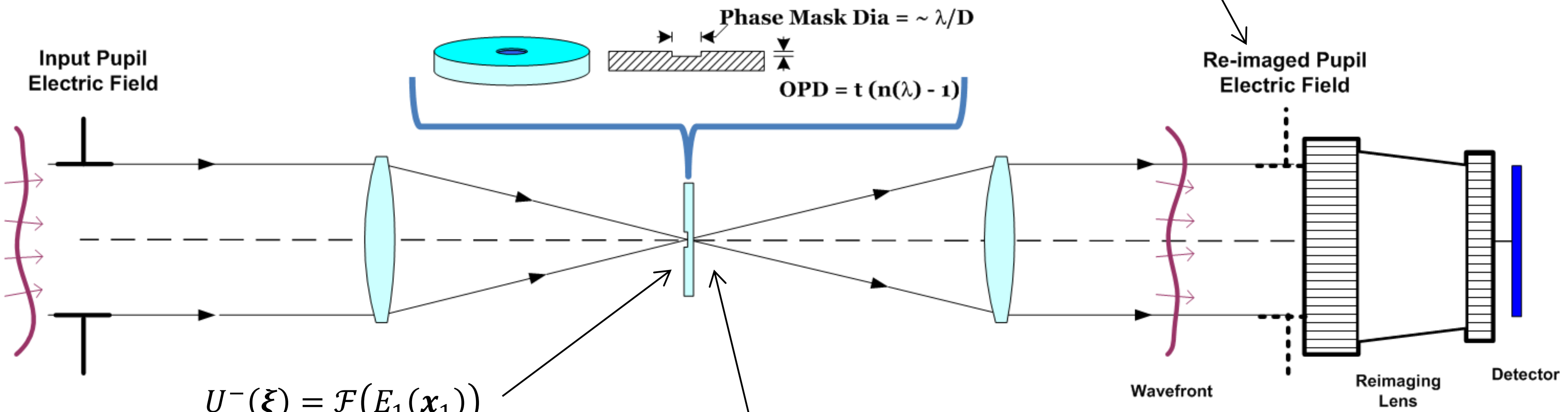
1. *Put a phase-dimple in an intermediate focal plane*
2. *Look at the subsequent pupil plane*

$$E_2(\boldsymbol{x}_2) = L[E(\boldsymbol{x}_1)]e^{i\theta_0} + (E(\boldsymbol{x}_1) - L[E(\boldsymbol{x}_1)])$$

$$L[E_1(\boldsymbol{x}_1)] = \mathcal{F}\left[\mathcal{F}(E_1(\boldsymbol{x}_1)) \cdot M\left(\frac{\rho}{a}\right)\right] = A_0 b(\boldsymbol{x}_2) e^{i\beta(\boldsymbol{x}_2)}$$

$$I_2(\boldsymbol{x}_2) = A_0^2\left(P^2(\boldsymbol{x}_2) + 2b^2(\boldsymbol{x}_2) + 2b(\boldsymbol{x}_2)P(\boldsymbol{x}_2)\left(sin(\phi(\boldsymbol{x}_2) - \beta(\boldsymbol{x}_2))\right) - cos(\phi(\boldsymbol{x}_2) - \beta(\boldsymbol{x}_2))\right)$$

$$E(u,v) = P(u,v)\cdot A(1+\varepsilon(u,v))e^{i\varphi(u,v)}$$



$$U^-(\boldsymbol{\xi}) = \mathcal{F}(E_1(\boldsymbol{x}_1))$$

$$U^+(\boldsymbol{\xi}) = \mathcal{F}(E_1(\boldsymbol{x}_1)) \cdot M\left(\frac{\rho}{a}\right) e^{i\theta_0} + \mathcal{F}(E_1(\boldsymbol{x}_1)) \cdot \left(1 - M\left(\frac{\rho}{a}\right)\right)$$

$$\phi(\boldsymbol{x}_2) - \beta(\boldsymbol{x}_2) = \frac{\pi}{4} + \text{ArcSin}\left[\frac{I_2(\boldsymbol{x}_2) - I_1(\boldsymbol{x}_2) - 2\,\boldsymbol{I}_{\boldsymbol{1,lf}}(\boldsymbol{x}_2)}{2\sqrt{2\,I_1(\boldsymbol{x}_2)\,\boldsymbol{I}_{\boldsymbol{1,lf}}(\boldsymbol{x}_2)}}\right]$$

Steeves, J. *et al.*, "Picometer Wavefront Sensing via the Phase-Contrast Technique", in prep.

Origin and Development

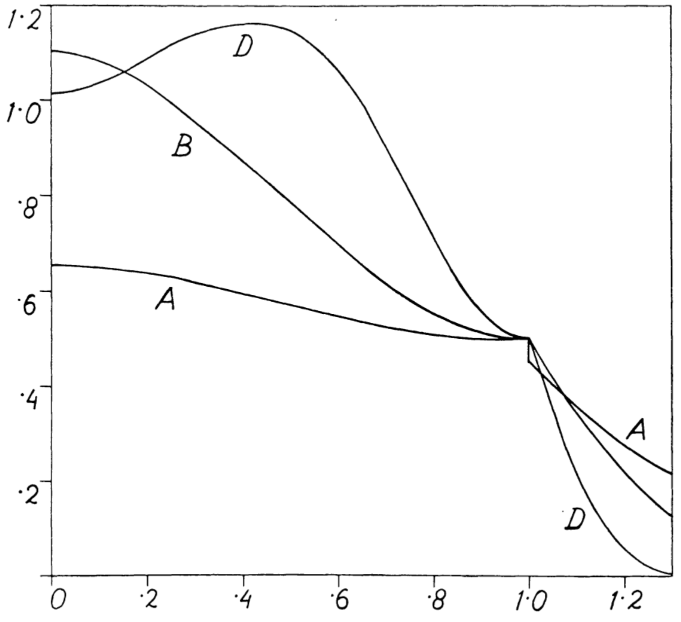


FIG. 3.

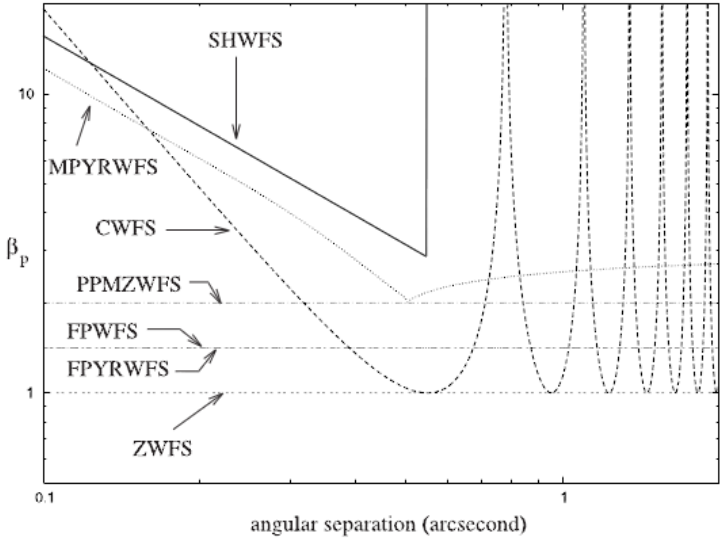
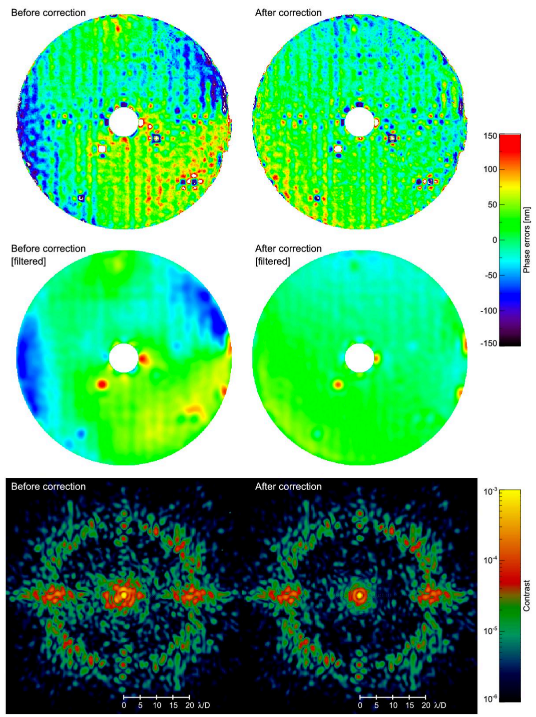


FIG. 10.—Value of β_p as a function of angular separation for the WFSs compared in this study. The WFSs were optimized for a separation of 0."5. For the SHWFS, $r_0 = 0.2$ m and $\lambda_0 = 0.5$ μm.

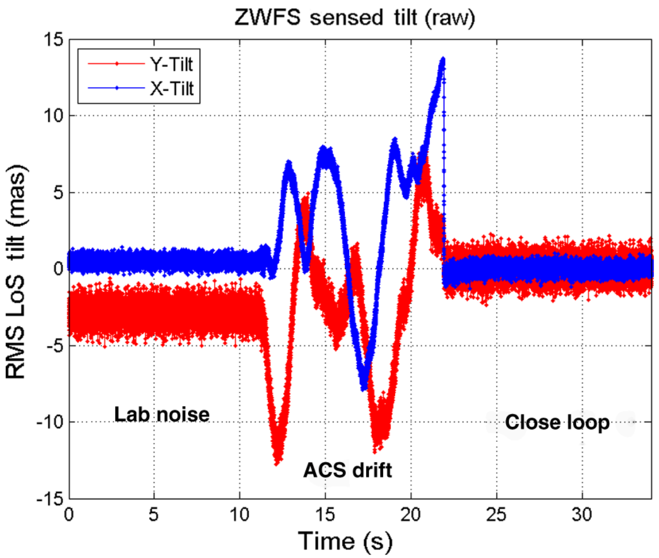


Zernike, F. Diffraction theory of the knife-edge test and its improved form the phase contrast method. *Mon. Notices Royal Astron. Soc.* 94, 377–384 (1934)

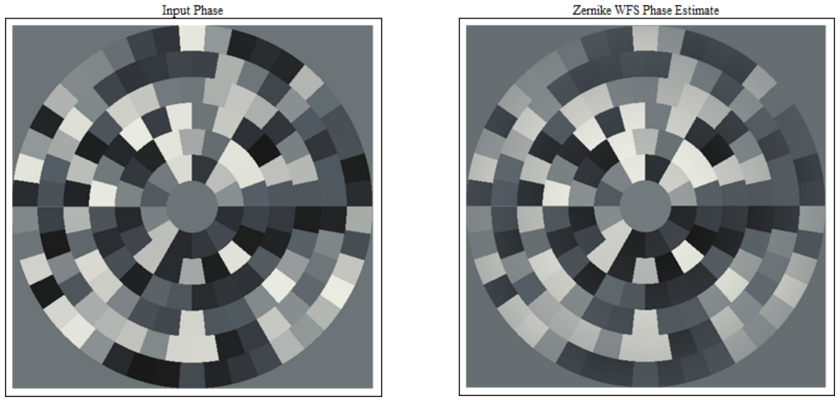
Guyon, O, "Limits of Adaptive Optics for High-Contrast Imaging", Ap. J, pp. 592 – 614 (2005).

N'Diaye, M. *et al.* Calibration of quasi-static aberrations in exoplanet direct-imaging instruments with a Zernike phase-mask sensor. II. Concept validation with ZELDA on VLT/SPHERE. *Astron. Astrophys.* 592, A79, DOI: 10.1051/0004-6361/ 201628624 (2016).

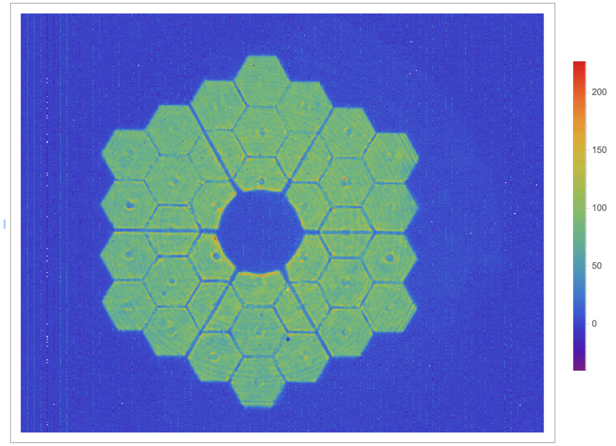
Applications



WFIRST-CGI Low-Order WFS



Phasing Segmented Apertures



Keck Planet Imager and Characterizer (KPIC)

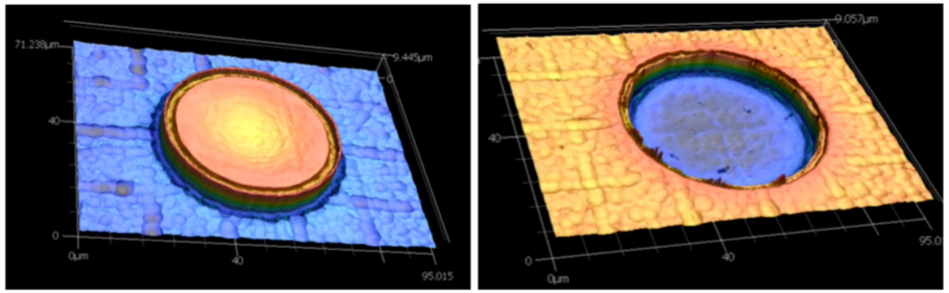
Shi, F. *et al.* Low-order wavefront sensing and control for WFIRST-AFTA coronagraph. *J. Astron. Telesc. Instrum. Syst.* 2, 1–19, (2016); DOI: 10.1117/1.JATIS.2.1.011021.

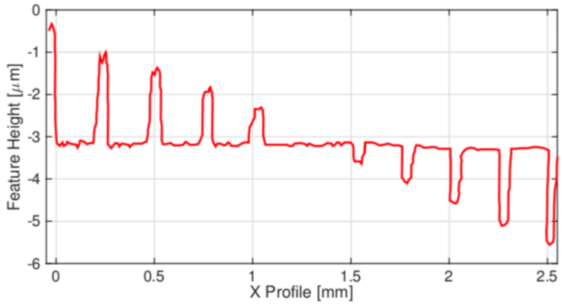
Wallace, J.K, “Common-path interferometric wavefront sensing for space telescopes ”, IEEE Aerospace Conference (2011)
DOI: 10.1109/AERO.2011.5747418.

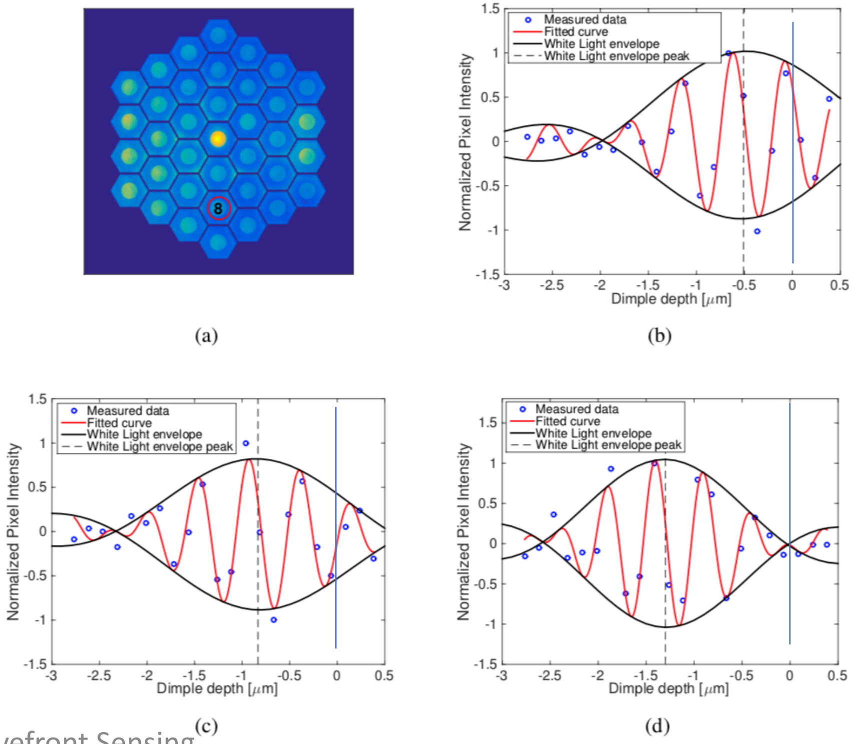
Mawet, *et al.*, “Keck Planet Imager and Characterizer: status update”, Proc. SPIE 10703, Adaptive Optics Systems VI, 1070306 (10 July 2018); doi: 10.1117/12.2314037

Limitations and Next Generation Devices

- A single-dimple is limited in sensing by the phase-dimple depth (or height)
- It’s possible to increase the dynamic range by having a series of dimples of different depth, and scanning the white light fringe.
- However, a device with +/- $\pi/2$ diversity helps.



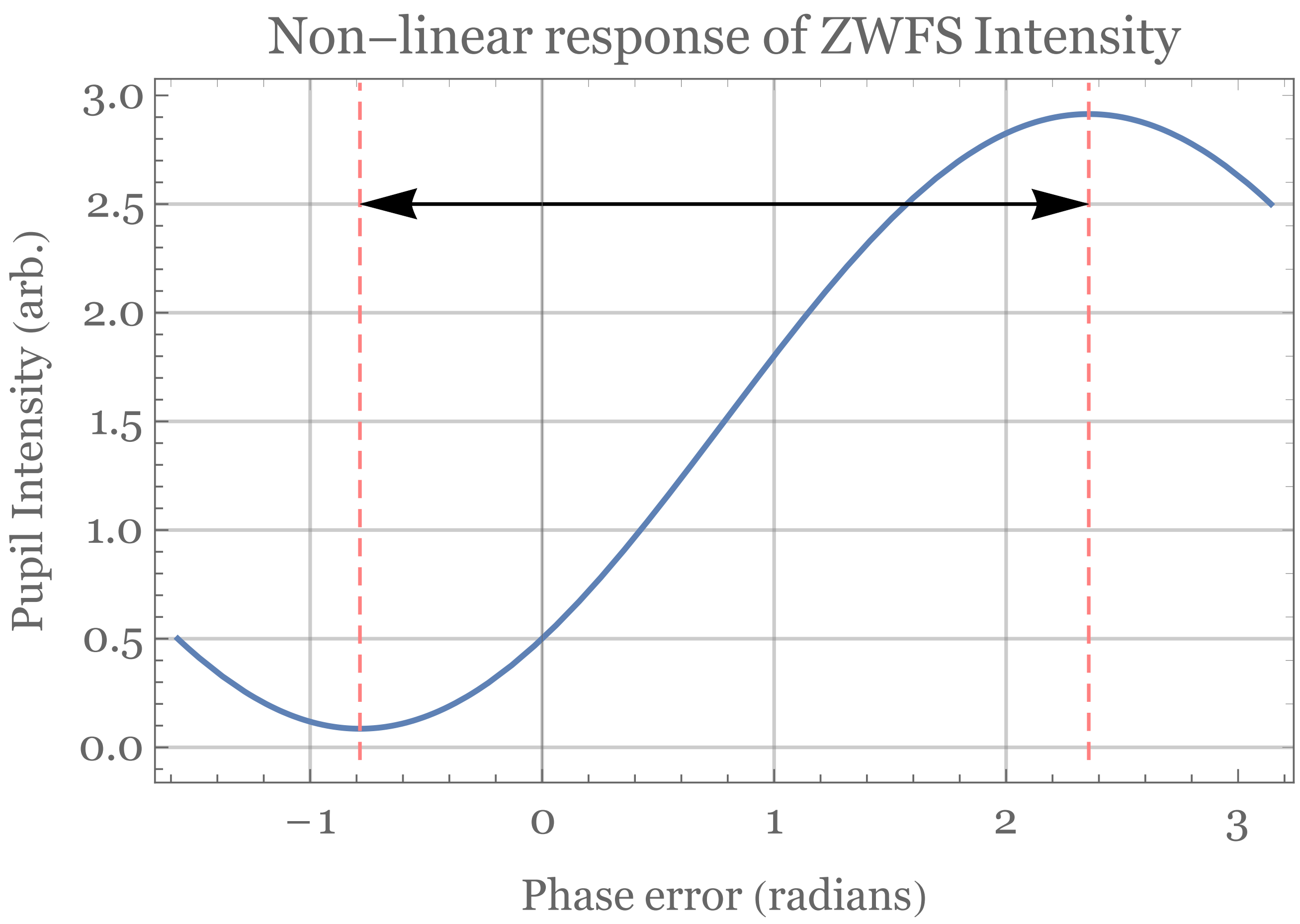




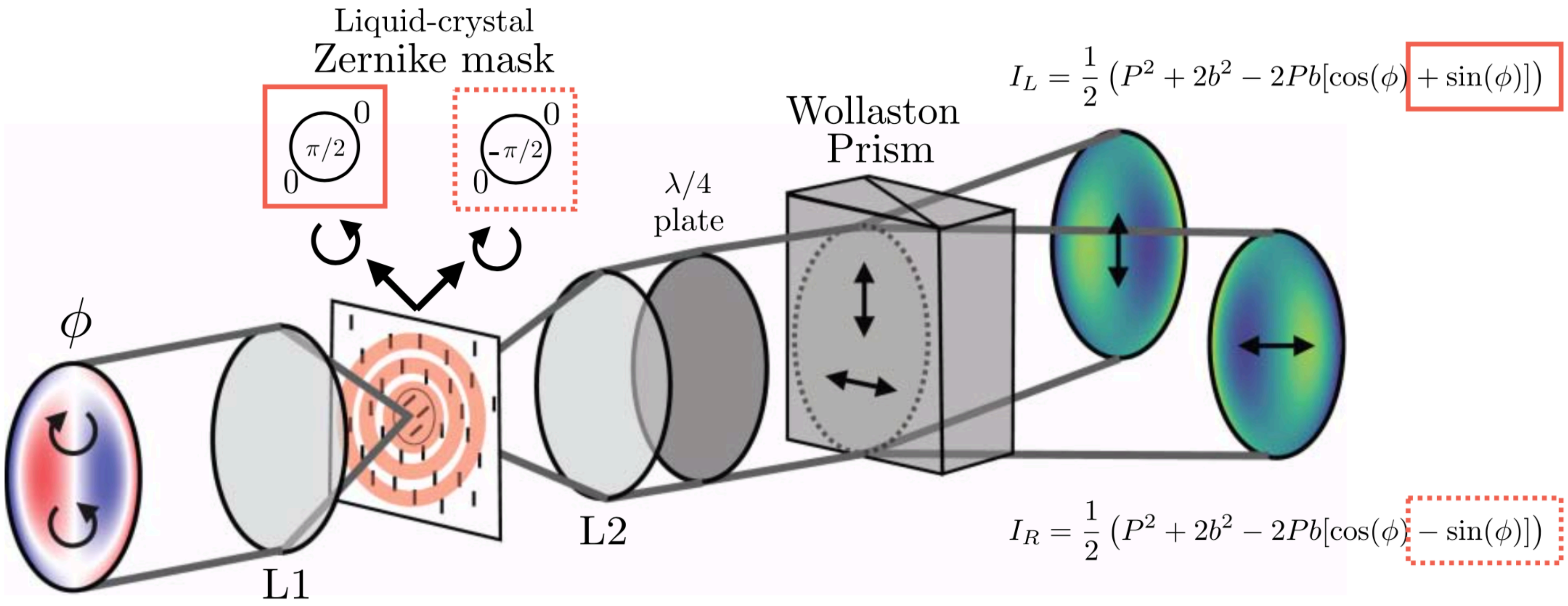
Jackson, Kate, *et al.* “Co-phasing primary mirror segments of an optical space telescope using a long stroke Zernike WFS”, Proc. SPIE 9904 (2016); doi: 10.1117/12.2231736

Limitations and Next Generation Devices

- Single Dimple has limited dynamic range.
- When the phase error gets too large, the brightness drops.
- Thus brightness can be associated with more than one phase error.
- Extra diversity can resolve this.



Vector Zernike with Liquid Crystal Devices

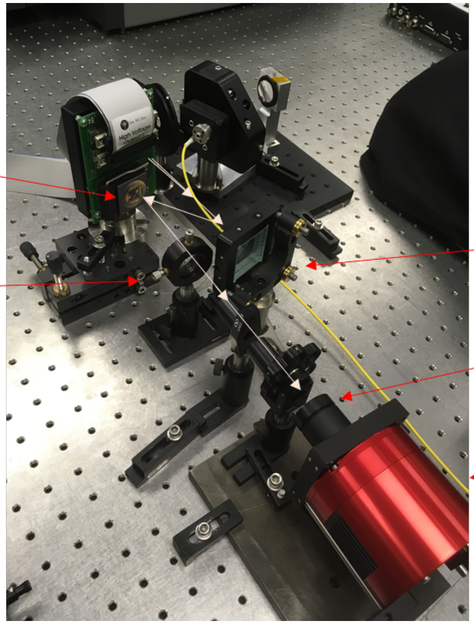


Doelman, D., *et al.*, "Simultaneous phase and amplitude aberration sensing with a liquid-crystal vector-Zernike phase mask", Optics Letters, **44** (1) pp. 17-20 (2019). https://doi.org/10.1364/OL.44.000017

Liquid Crystal vZWFS testing at JPL

Segmented Deformable Mirror

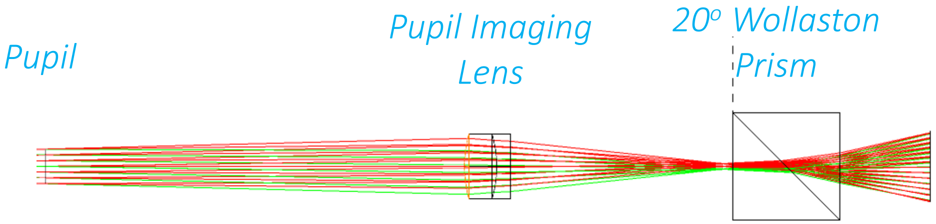
Vector Zernike Focal plane mask (liquid crystal)

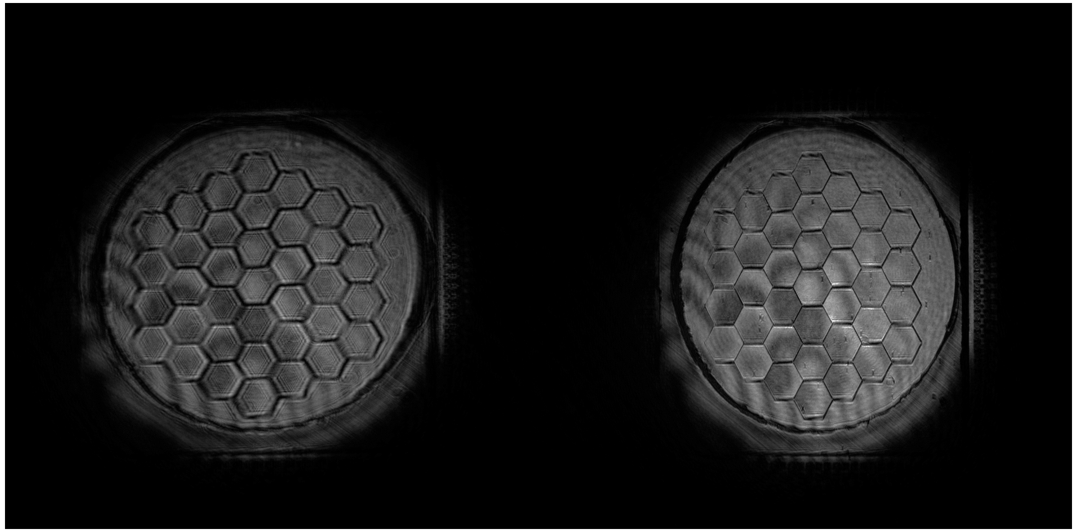


Focusing Off-axis Parabolic Mirror

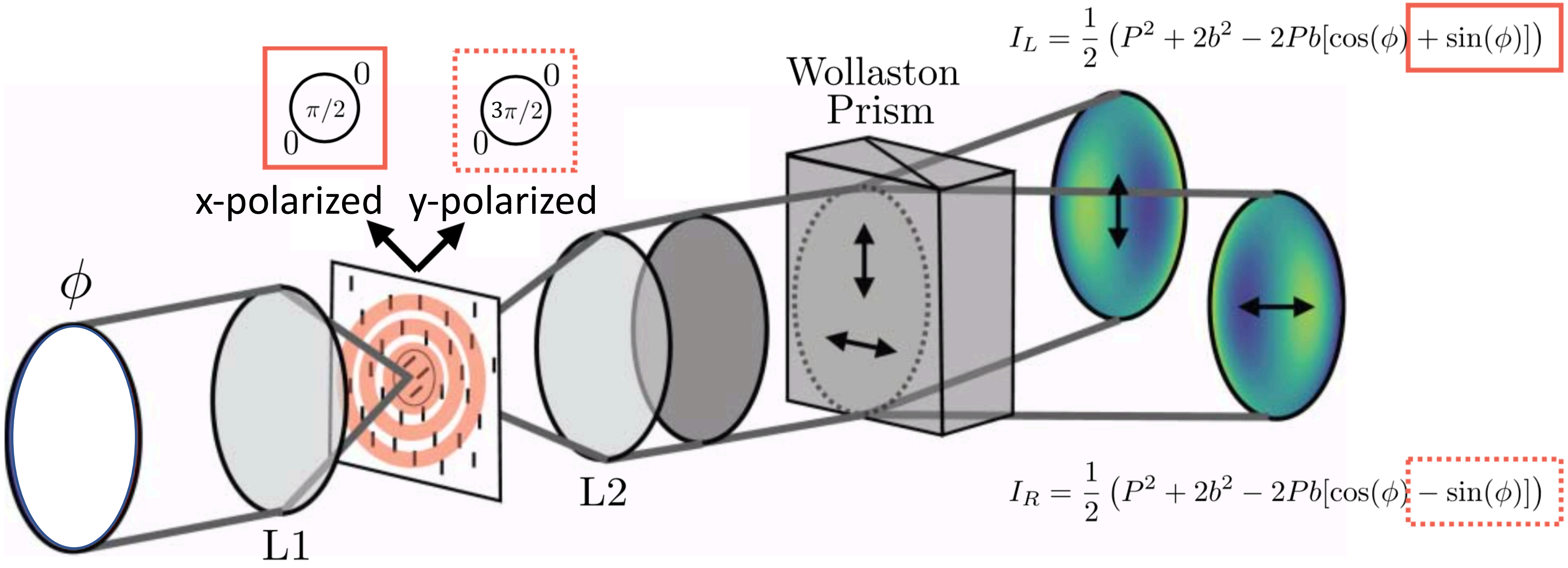
Quarter waveplate plate + Wollaston Prism

CMOS Camera



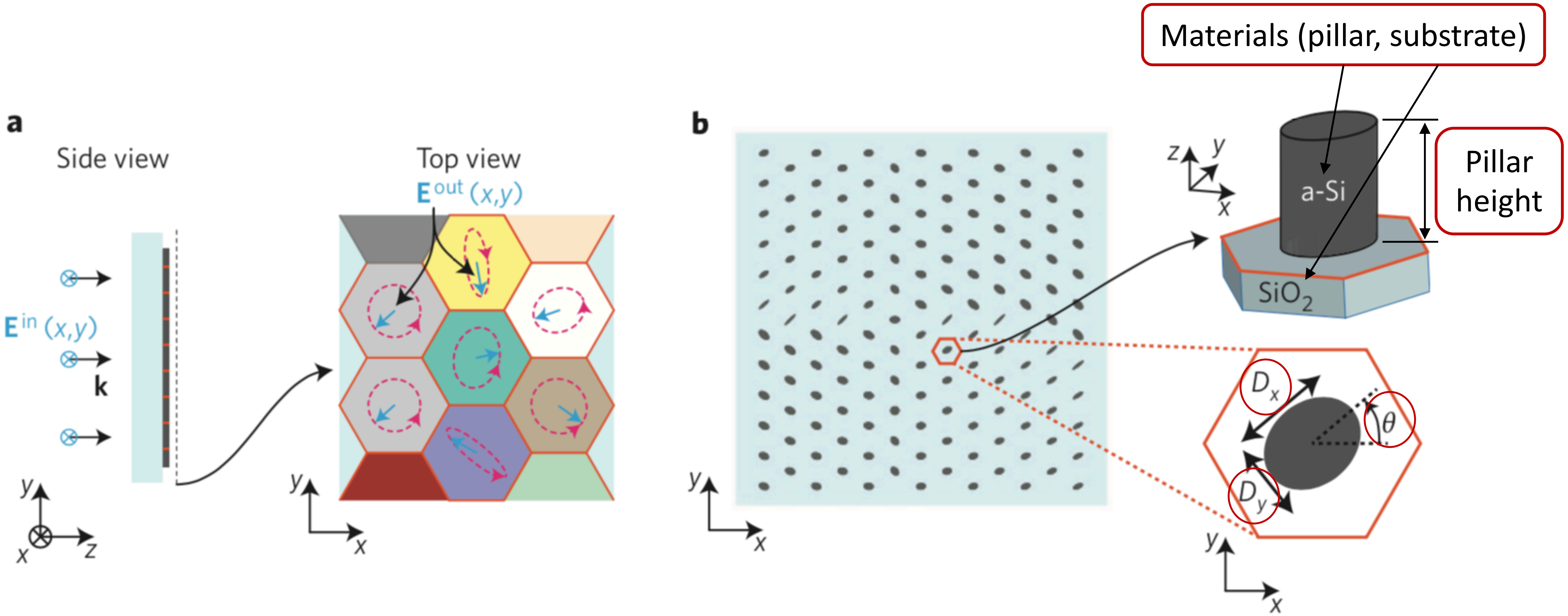


Vector Zernike with Metasurface Optics



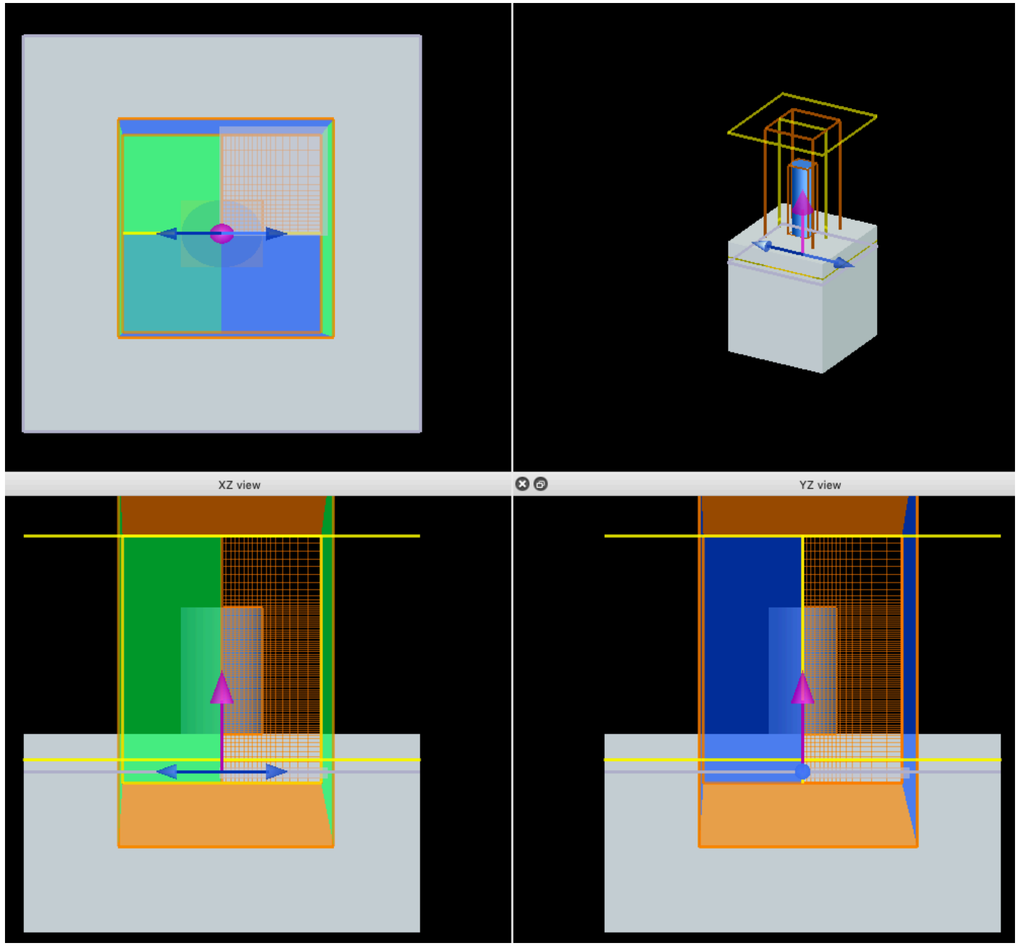
Device operation requires phase shift over a Ø 23.8 µm domain with $\varphi_x = \pi/2$ for x-polarized and $\varphi_y = 3\pi/2$ for y-polarized light with respect to the unpatterned substrate

Metasurface Optics



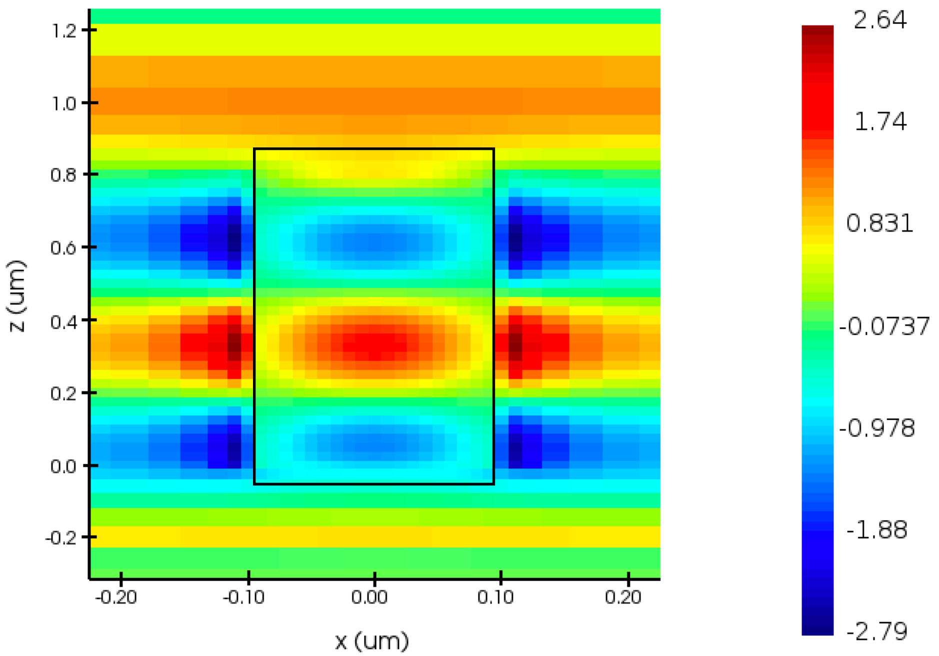
Arbabi, Amir, *et al.*, "Dielectric metasurfaces for the complete control of phase and polarization with subwavelength spatial resolution and high transmission", Nature Nanotechnology, Vol. 10, pp. 937 – 944 (2015); DOI: 10.1038/NNANO.2015.186

Finite Difference Time Domain Simulations

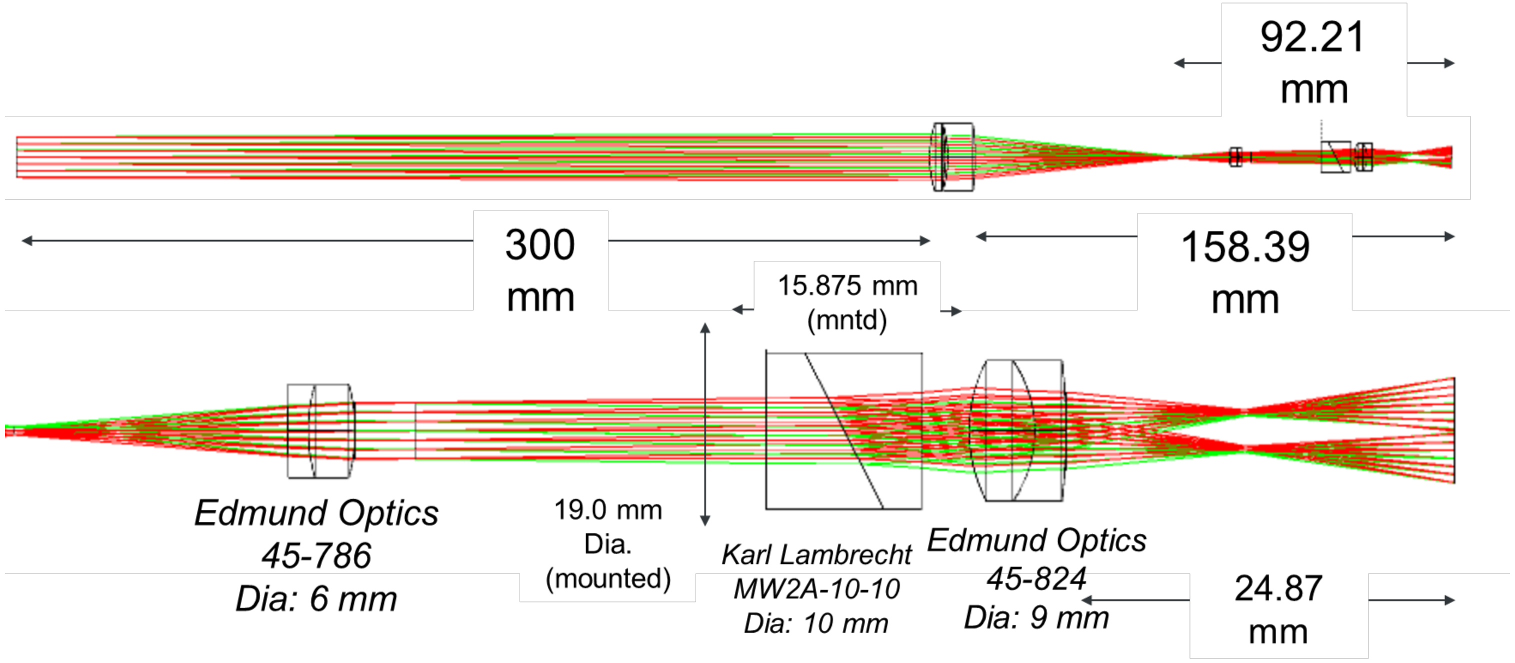


- Software tool ***Lumerical*** to solve Maxwell's equations of light propagation

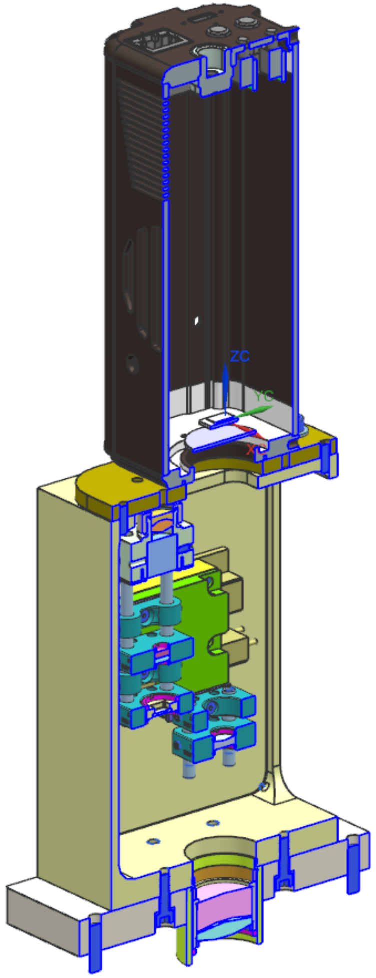
$Re(E_x)$



Application to KPIC



Optical Design



Mechanical Design

Impact of the ZWFS

- ZWFS has demonstrated itself to be a simple and robust method of measuring very small phase errors in optical systems.
  - It's application to high-contrast imaging is a great match of both implementation and capability to need.
- Development of new devices will enhance its capabilities in both extending the dynamic range and increasing sensitivity.

The Future

- It's time to take a different perspective, one that is more systems level.
- If we use a ZWFS to continuously monitor the wavefront in a high-contrast system, how might we use this capability to reduce requirements on the overall system?
- In particular, consider relaxing stringent requirements on DM's and optical alignment.
- The Zernike WFS may not simply aide in establishing and maintaining high contrast, it may be *essential* for architecting these systems by enabling a new trade space.

Thank you for your time and attention.