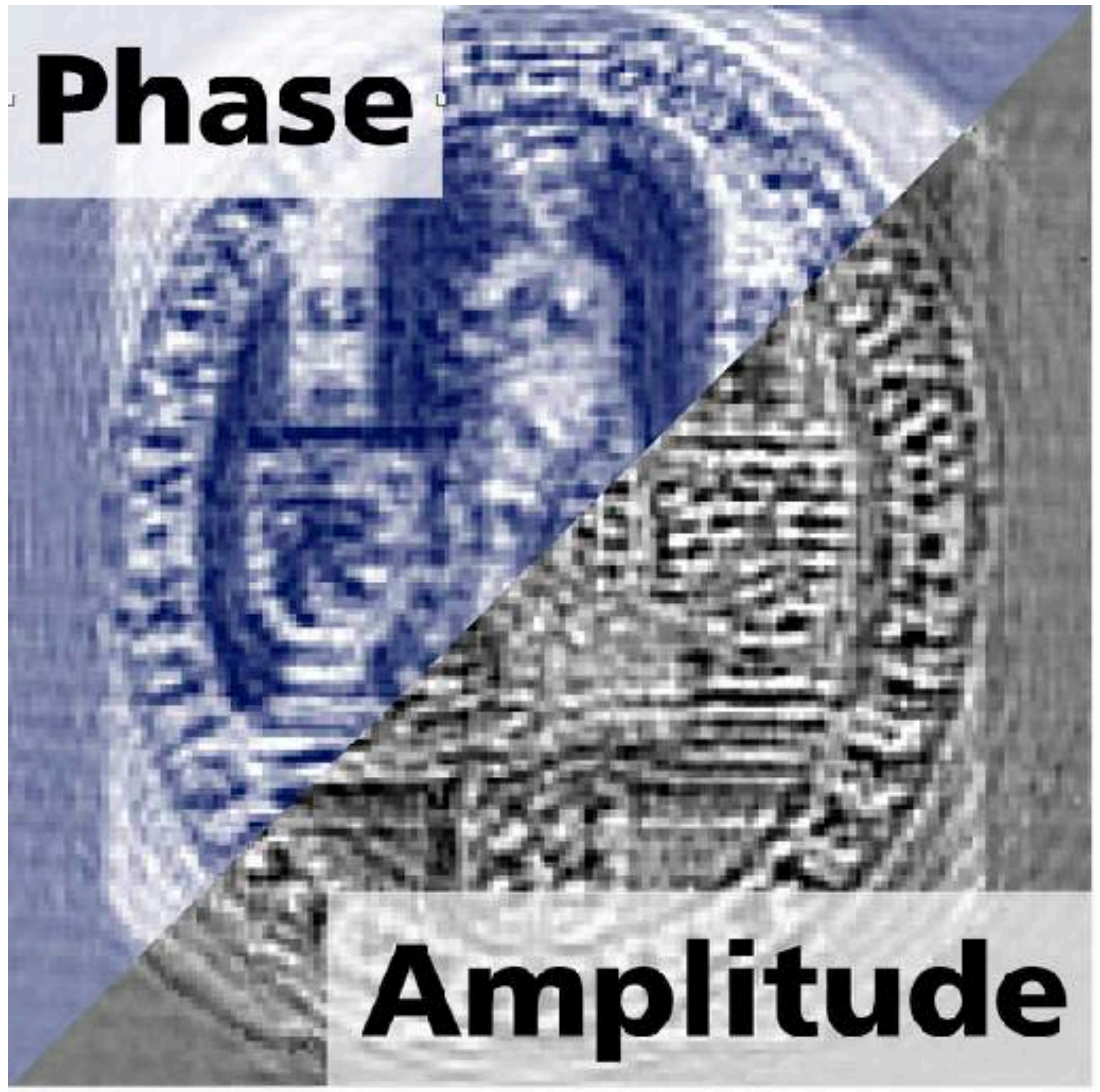
The vector-Zernike wavefront sensor



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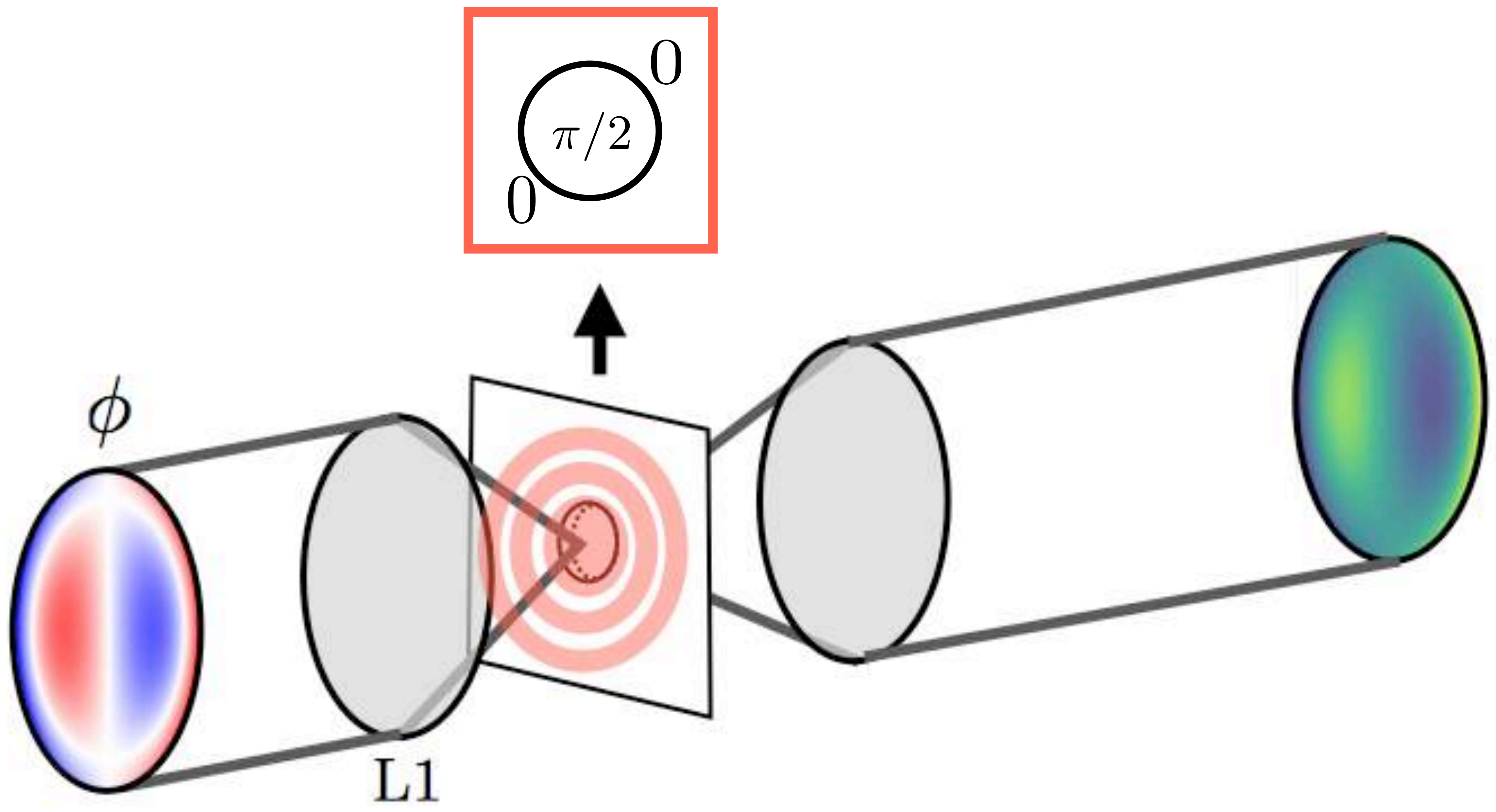
The Zernike wavefront sensor



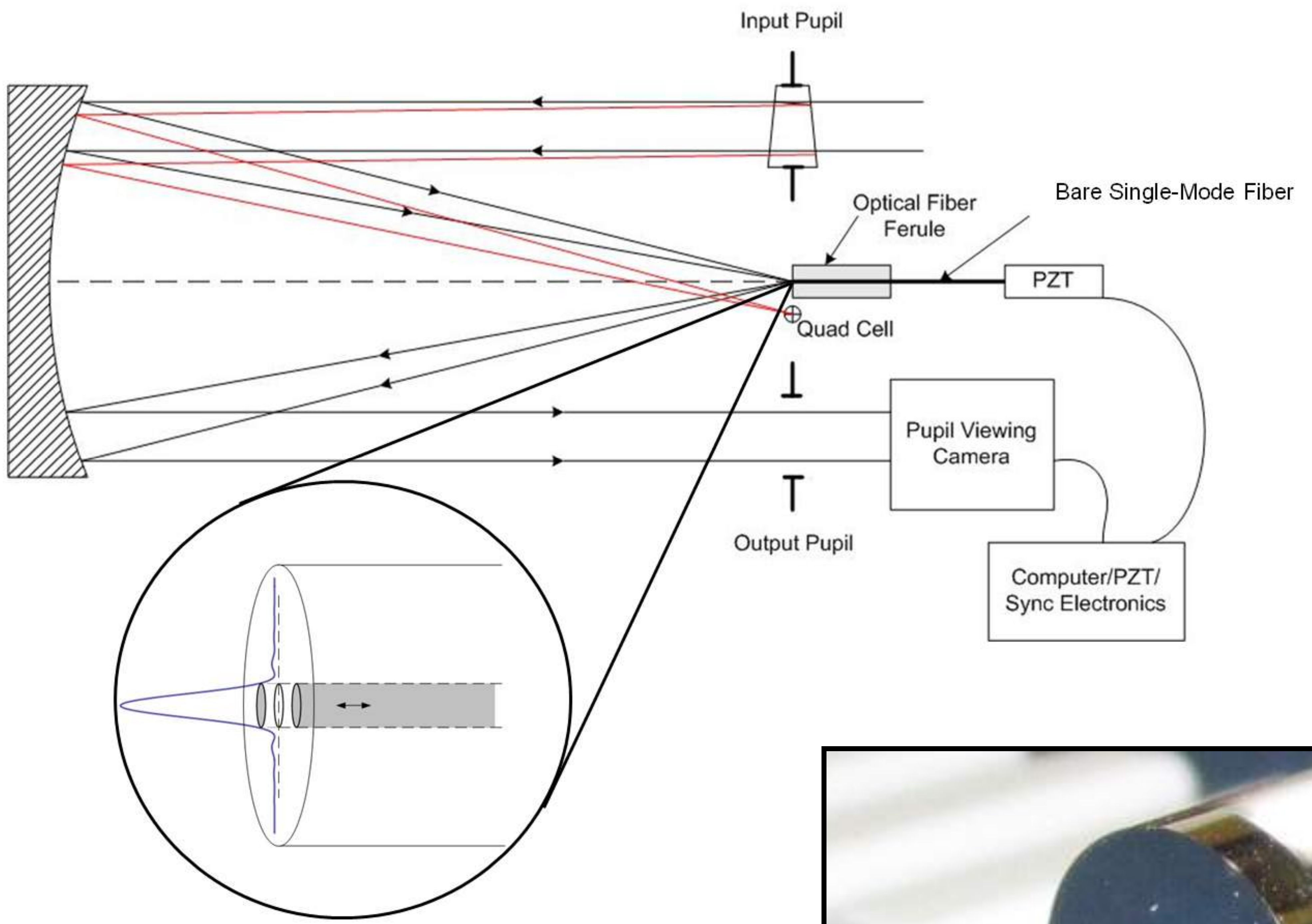
- Phase aberrations are converted to intensity variations in the conjugated pupil plane
- Most sensitive wavefront sensor (Guyon 2005)

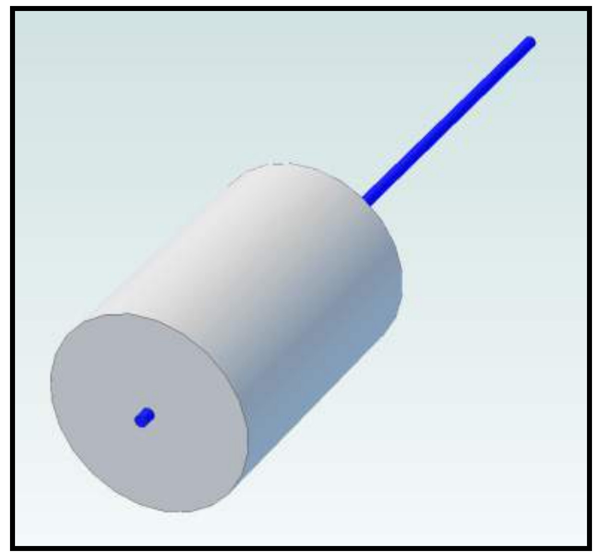
- Limited dynamic range
- Varying amplitude variations reconstructed as phase aberrations

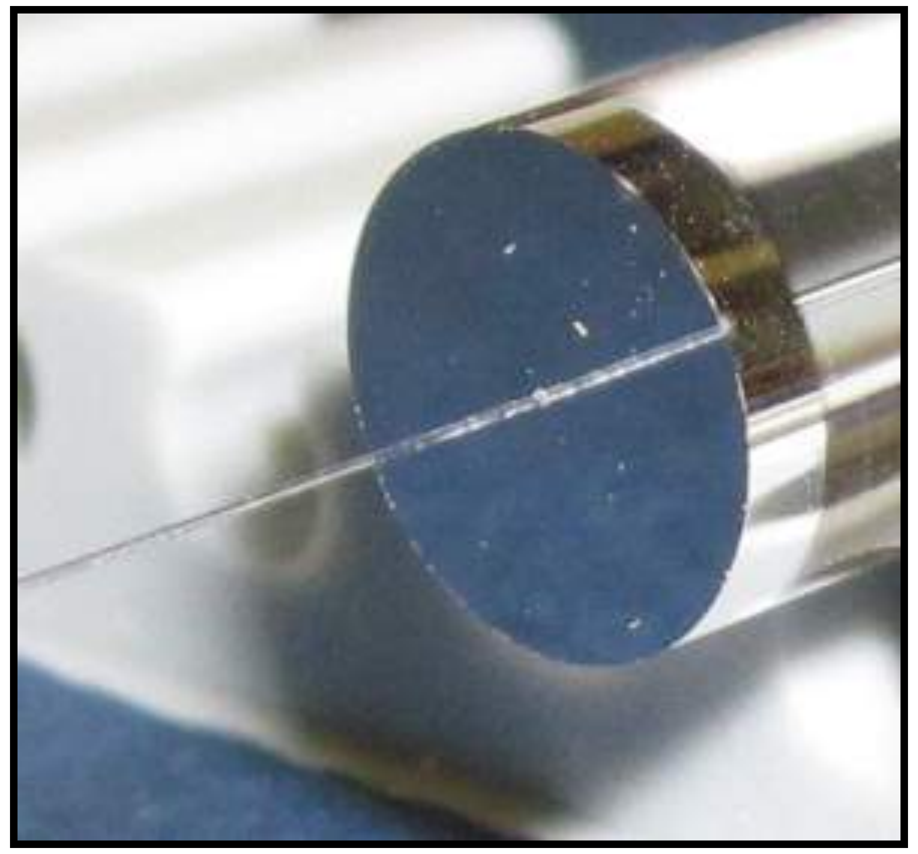
Phase-Shifting Zernike Interferometer Wavefront Sensor

- Zernike mask consists of silver-coated single-mode fiber with moving optical capillary tube.

- With four phase steps (-π/2, 0, π/2 and π), both phase and amplitude of the wavefront can be recovered







Wallace et al. 2011

Phase-Shifting Zernike Interferometer Wavefront Sensor

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$$I_1 = E_1 \cdot E_1^* = A^2(1+\varepsilon^2 - 2\phi + \phi^2)$$

$$I_2 = E_2 \cdot E_2^* = A^2(1+\varepsilon^2 + 2\varepsilon + \phi^2)$$

$$I_3 = E_3 \cdot E_3^* = A^2(1+\varepsilon^2 + 2\phi + \phi^2)$$

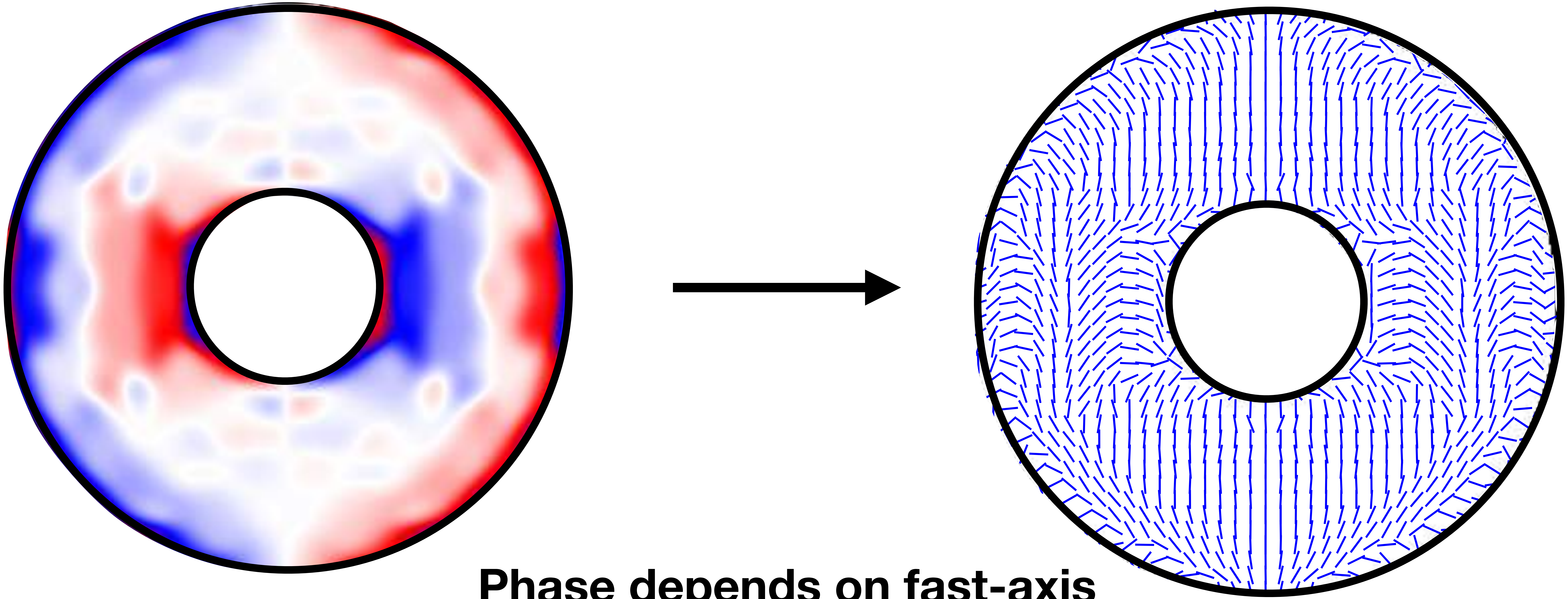
$$I_4 = E_4 \cdot E_4^* = A^2(1+\varepsilon^2 - 2\varepsilon + \phi^2)$$

$$I_0 = (I_1 + I_2 + I_3 + I_4)/4.$$

$$\phi = \frac{I_3 - I_1}{4I_0} \qquad \varepsilon = \frac{I_2 - I_4}{4I_0}$$

Wallace et al. 2011

Liquid-crystal technology: the geometric phase



Phase depends on fast-axis orientation in a half-wave retarder and circular polarization state

Geometric phase

$\frac{\lambda}{2}$-plate

Geometric phase

Geometric phase

Geometric phase

Geometric phase

Geometric phase

$$\theta = \pm 2\alpha$$

Geometric phase

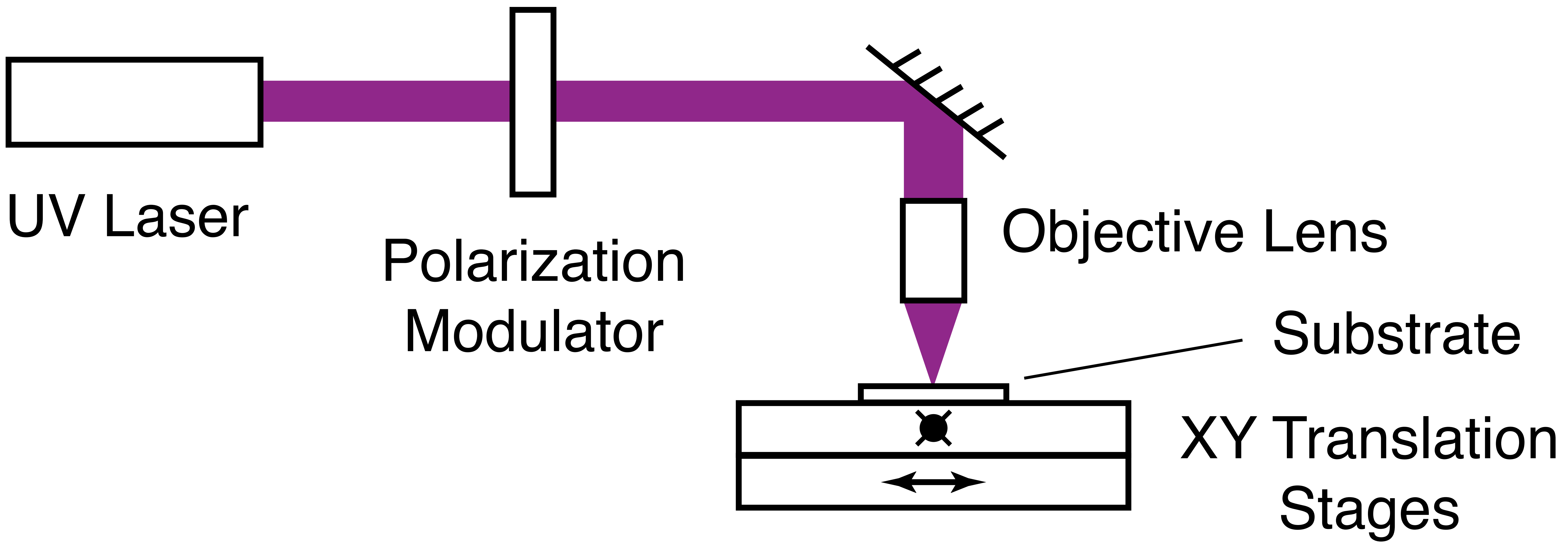
$$\theta = \pm 2\alpha$$

Geometric phase

$$\theta = \pm 2\alpha$$

liquid-crystal freeform optics

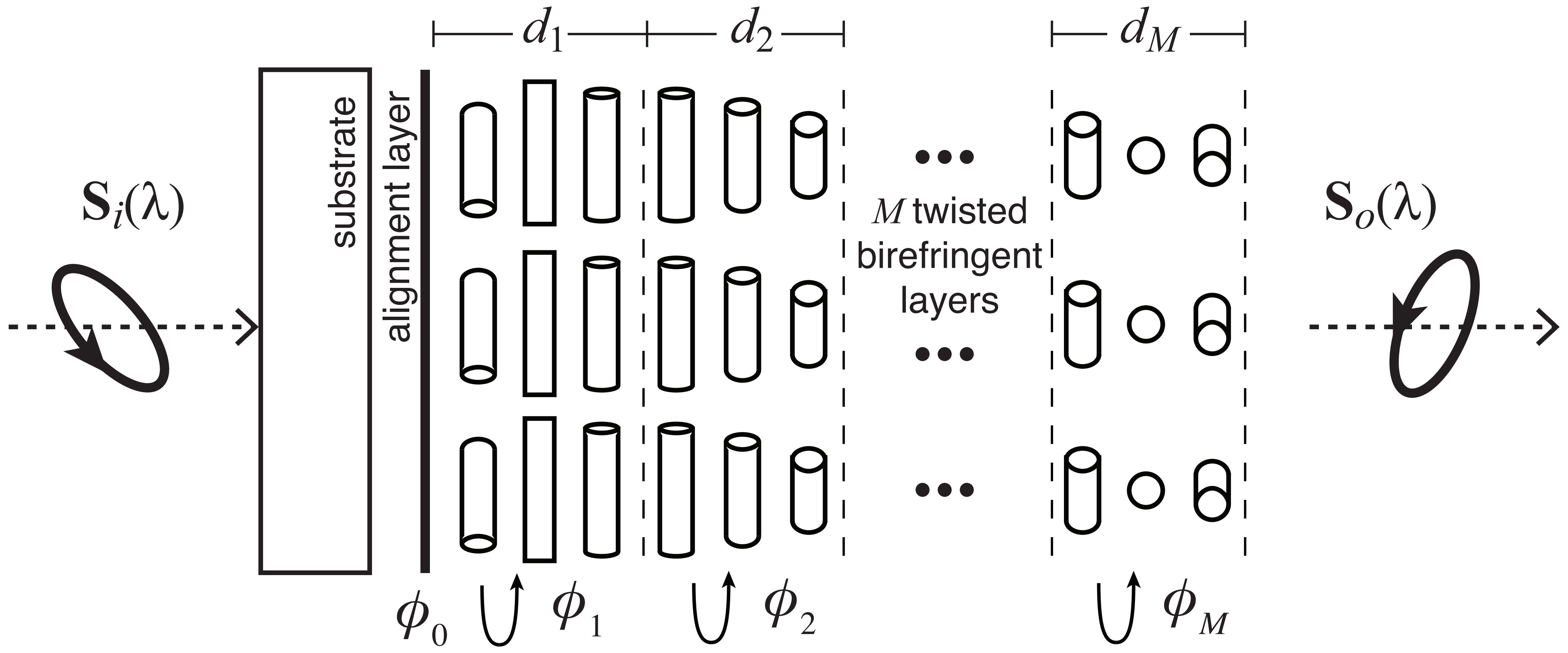
1. **any phase pattern** thanks to direct-write technique

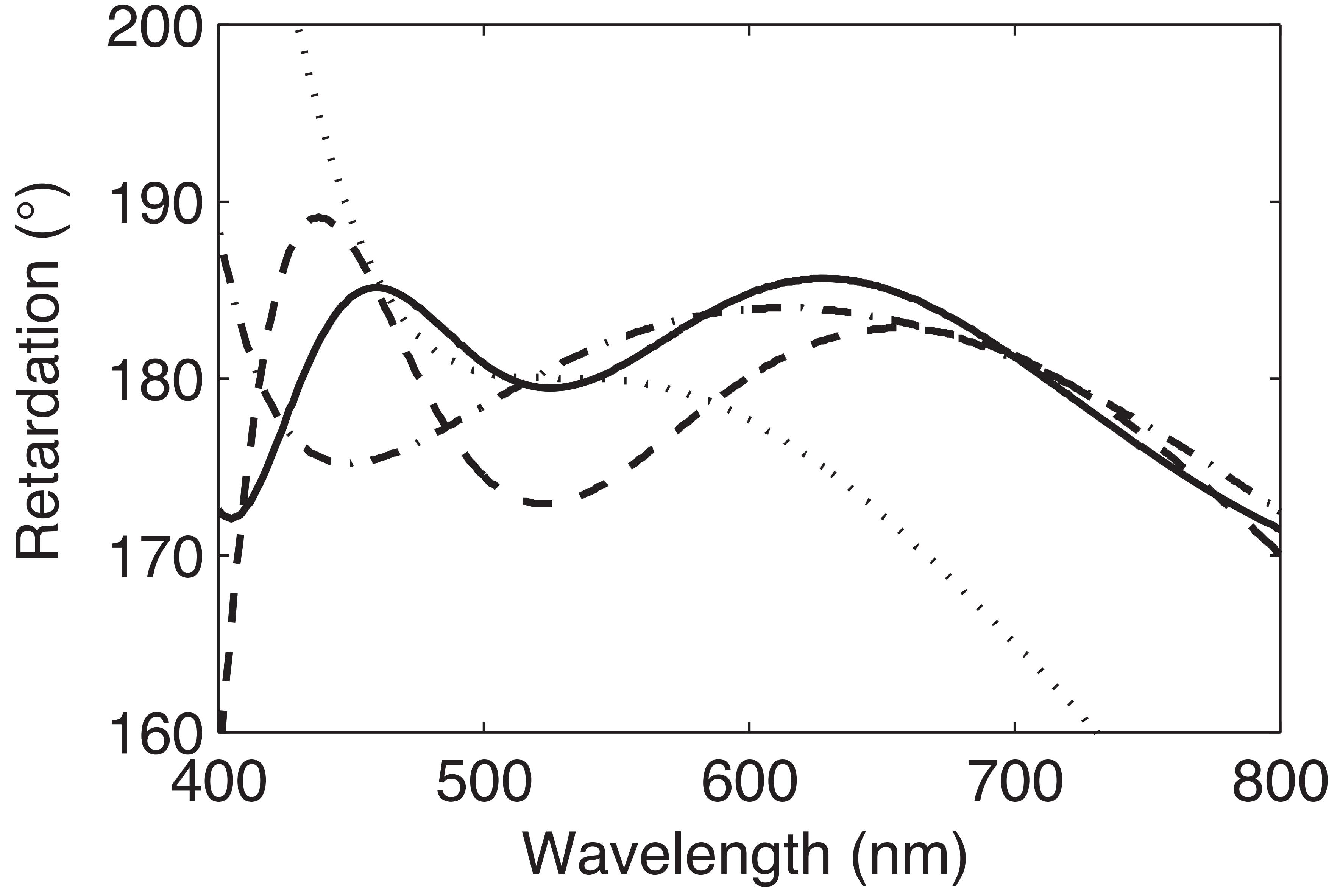


Miskiewicz & Escuti (2014)

liquid-crystal freeform optics

2. **achromatization** thanks to self-aligning multi-twist liquid crystal retarder

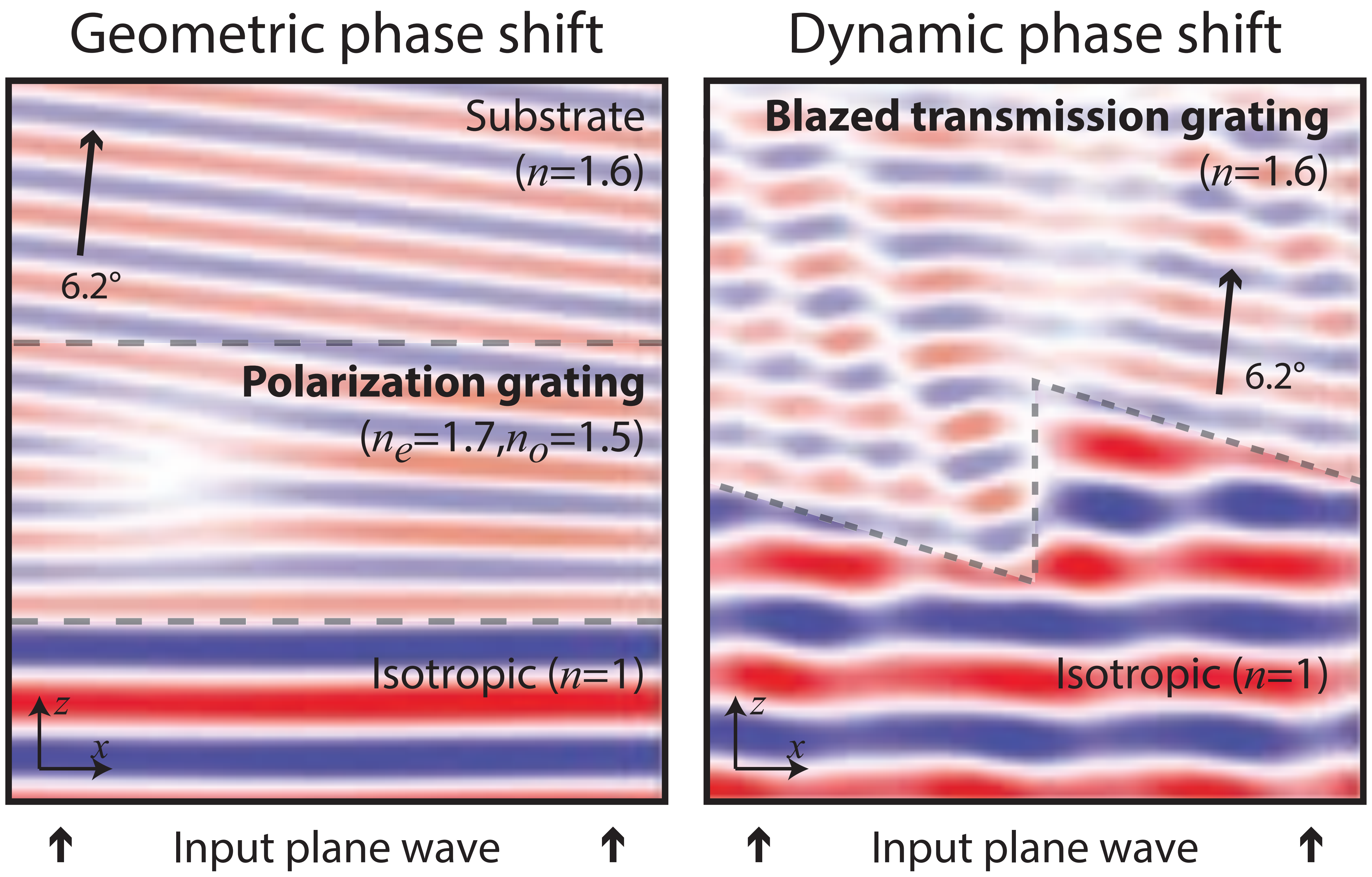




Komanduri et al. (2013)

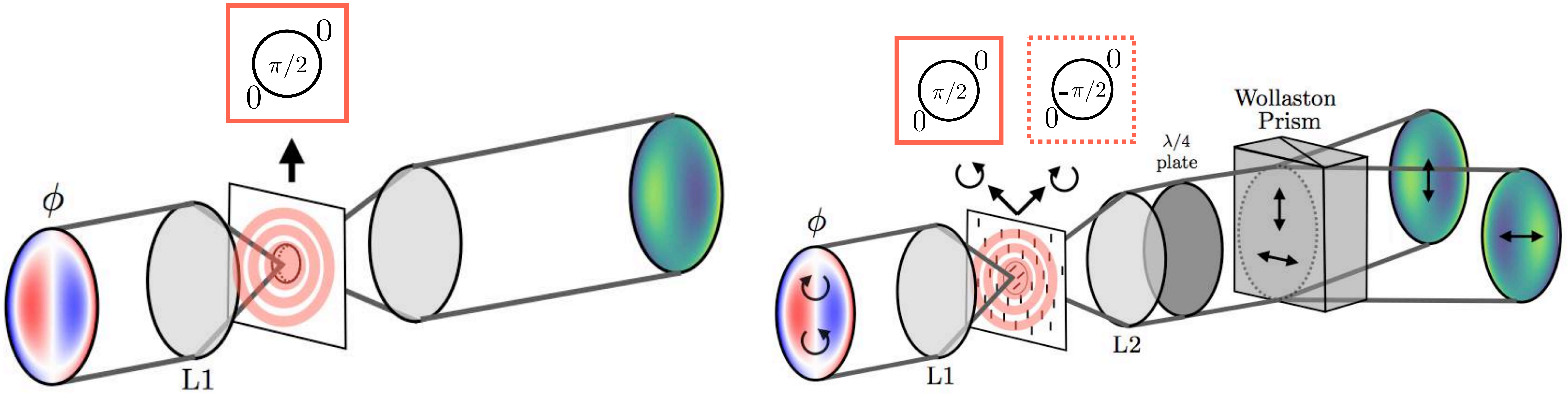
liquid-crystal freeform optics

3. **very local** and **efficient phase ramps**

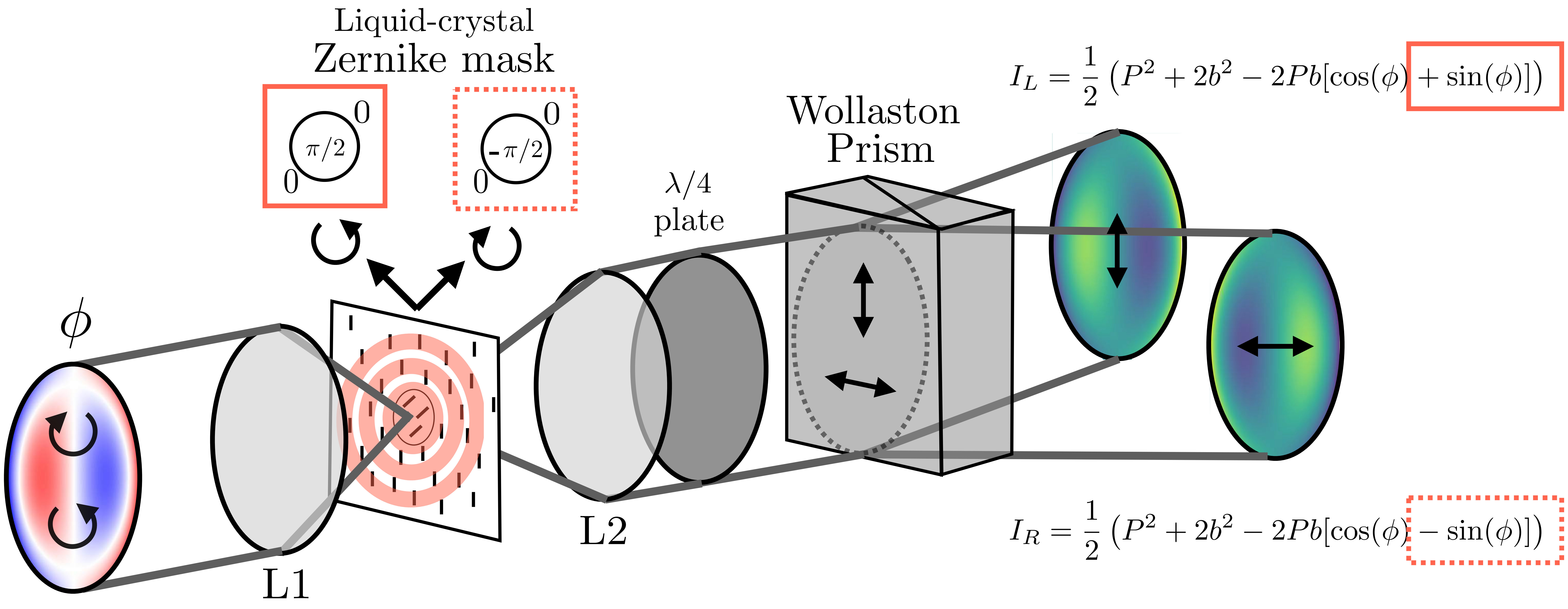


Escuti et al. (2016)

The vector-Zernike wavefront sensor



Wavefront reconstruction theory



Wavefront reconstruction theory

Incoming wavefront

$$\Psi_A = Pe^{i\phi} = P_0(1-\epsilon)e^{i\phi}$$

Pupil intensities

$$I_L = \frac{1}{2}(P^2 + 2b^2 - 2Pb[\cos(\phi) + \sin(\phi)])$$

$$I_R = \frac{1}{2}(P^2 + 2b^2 - 2Pb[\cos(\phi) - \sin(\phi)])$$

$$b = \widehat{M} \otimes \Psi_A \simeq \sqrt{S}\widehat{M} \otimes P_0 = \sqrt{S}b_0$$

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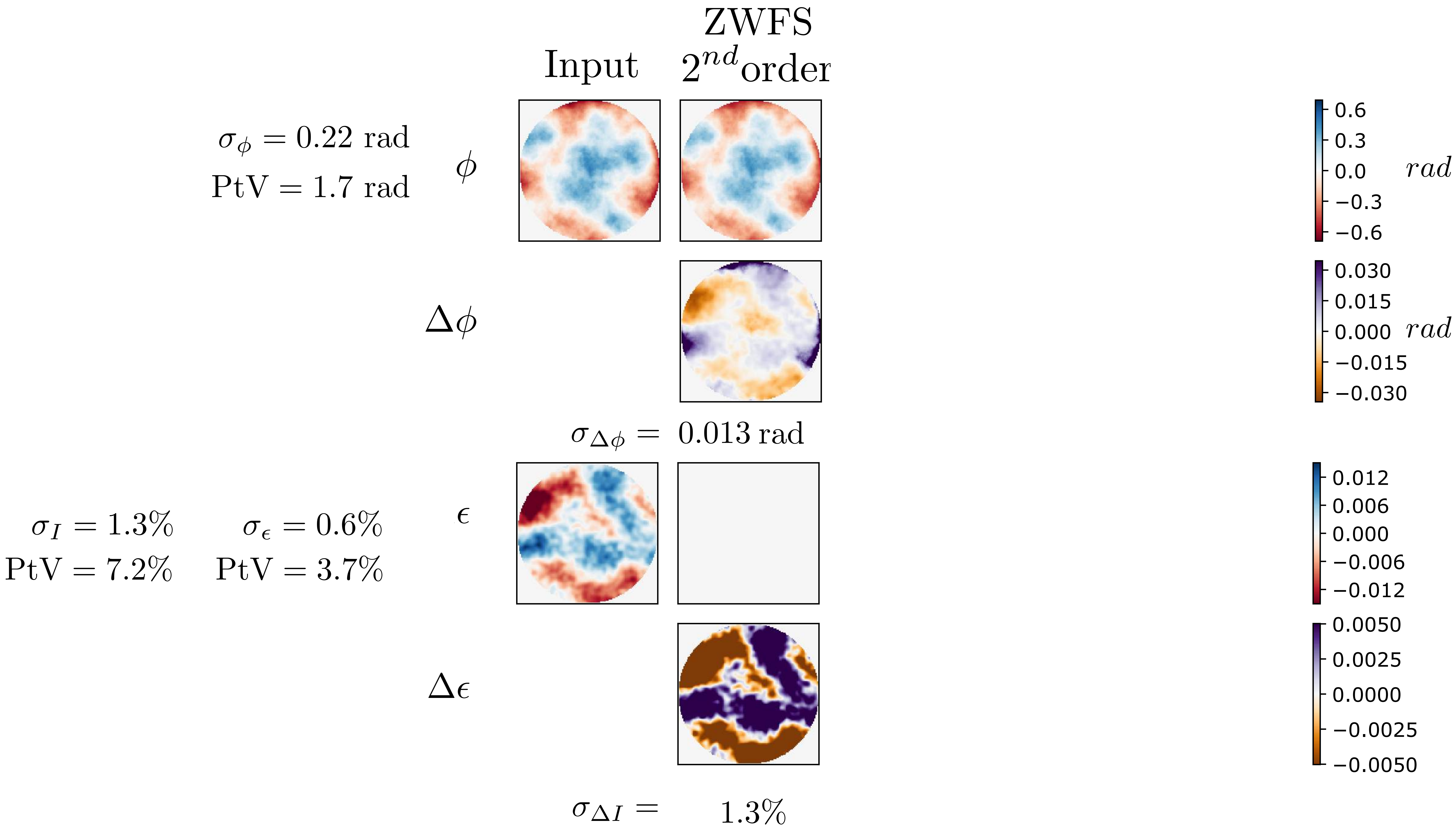
Reconstruction

$$P = \sqrt{I_R + I_L + \sqrt{4b^2(I_R + I_L) - (I_R + I_L)^2 - 4b^4}}$$

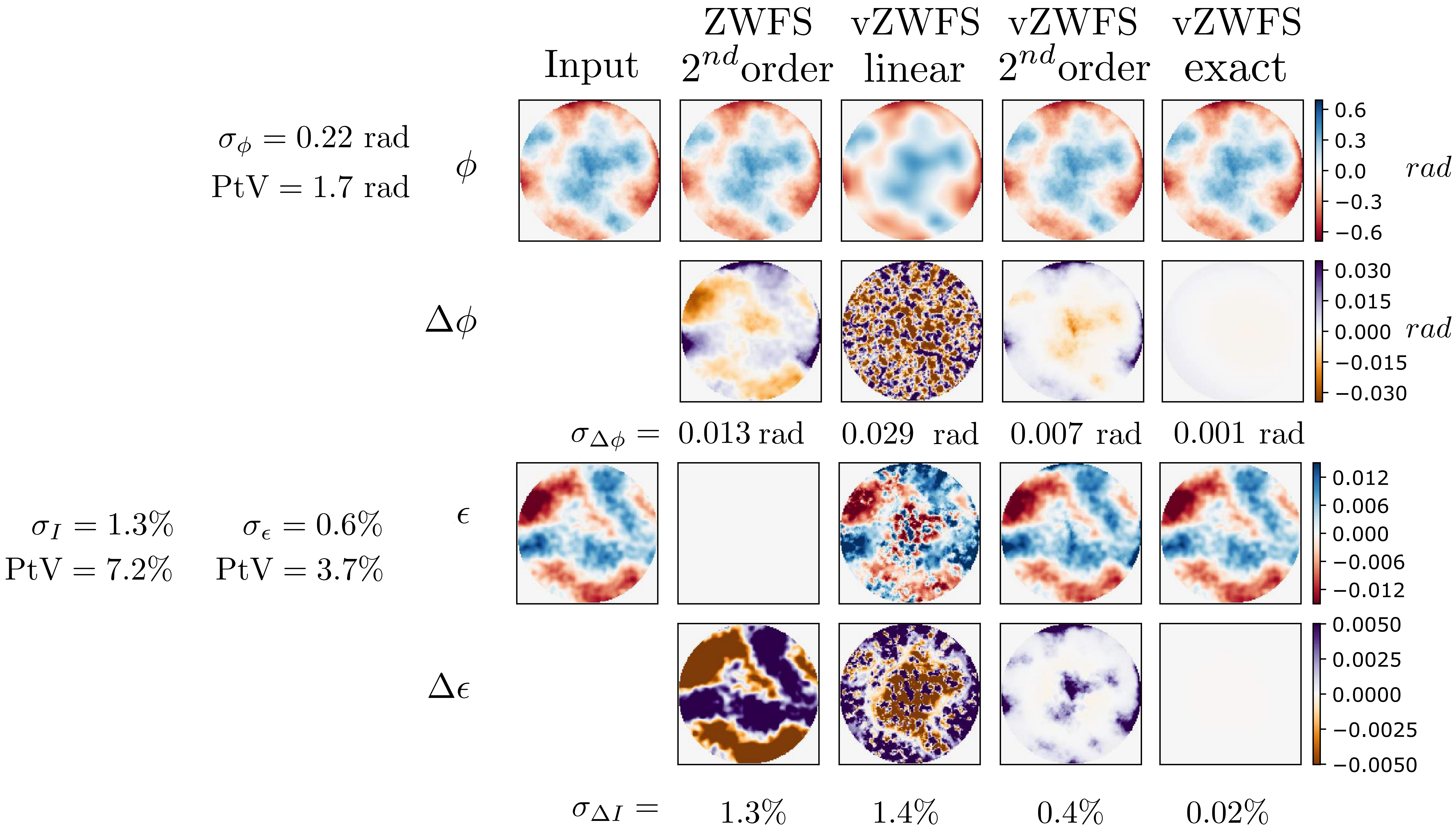
$$\phi = \arcsin\left(\frac{I_R - I_L}{2Pb}\right)$$

Nested solution! -> approximate with b_0 and iterate

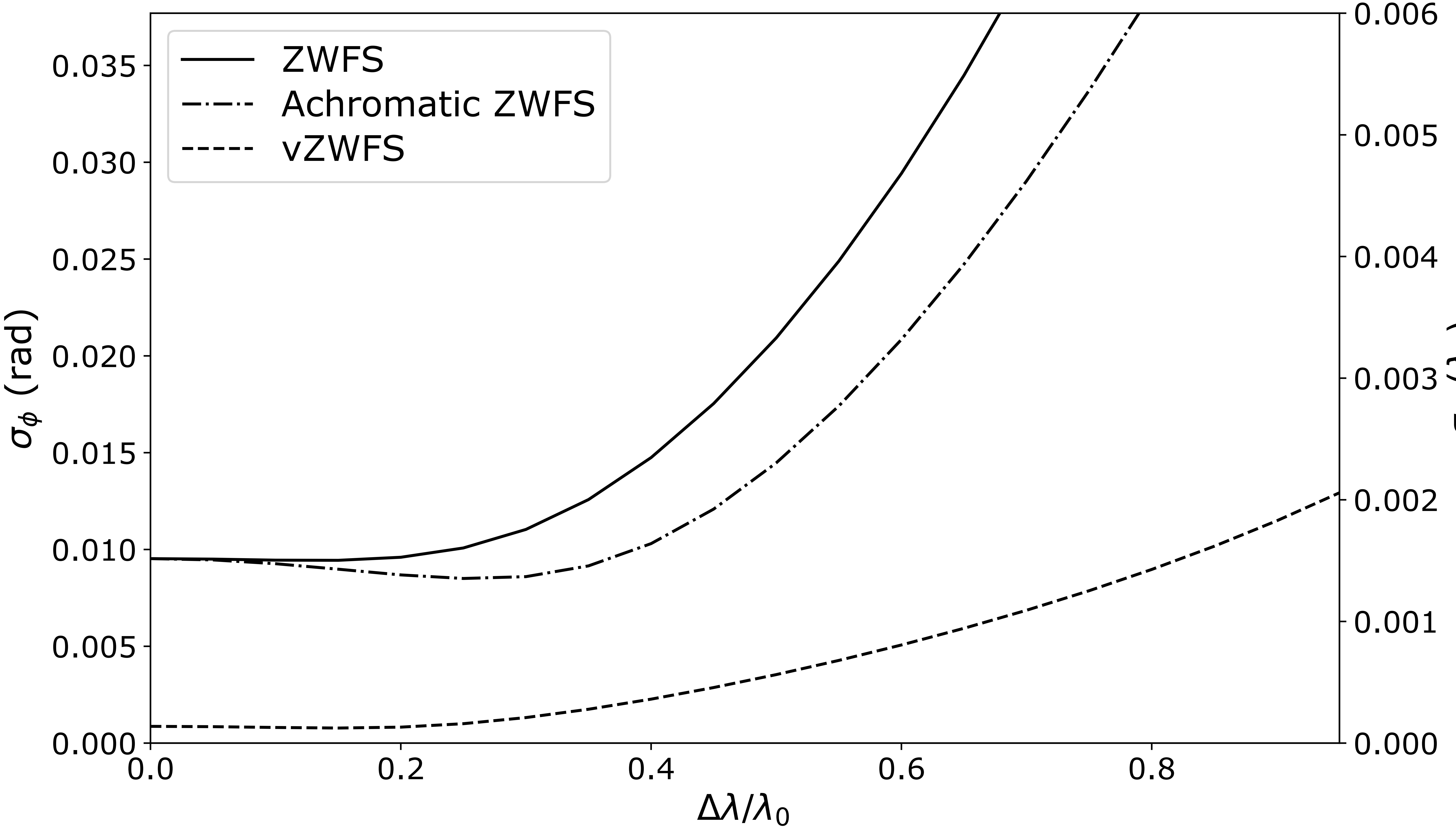
Simultaneous phase and amplitude reconstruction



Simultaneous phase and amplitude reconstruction



Broadband performance



HCIPy polarization update

```
vZWFS_ideal = VectorZernikeWavefrontSensorOptics(pupil_grid, num_pix=128)
```

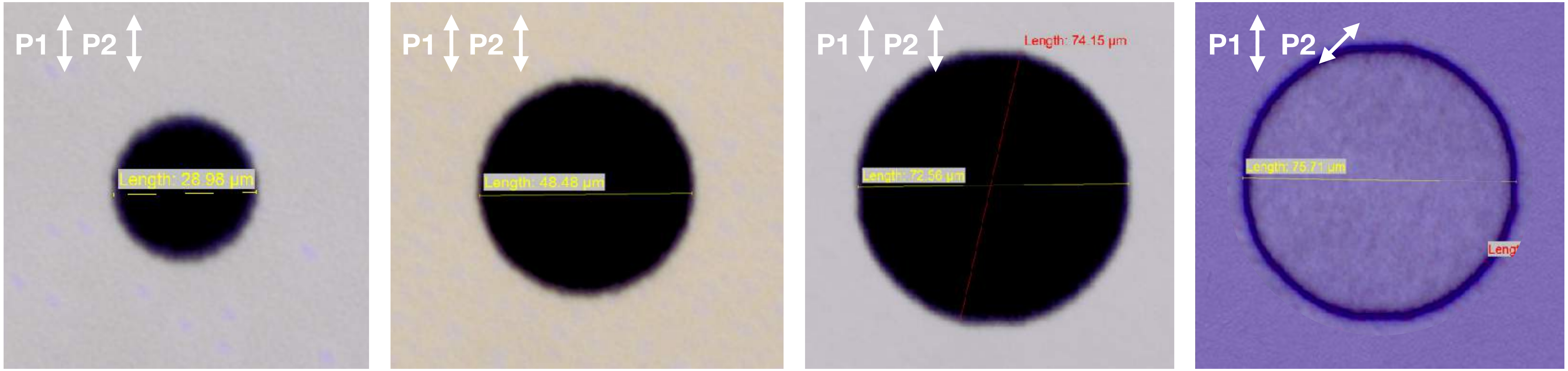
```
amp_est, phase_est = reconstructor(vZWFS_ideal(wf_new))
```

https://github.com/ehpor/hcipy

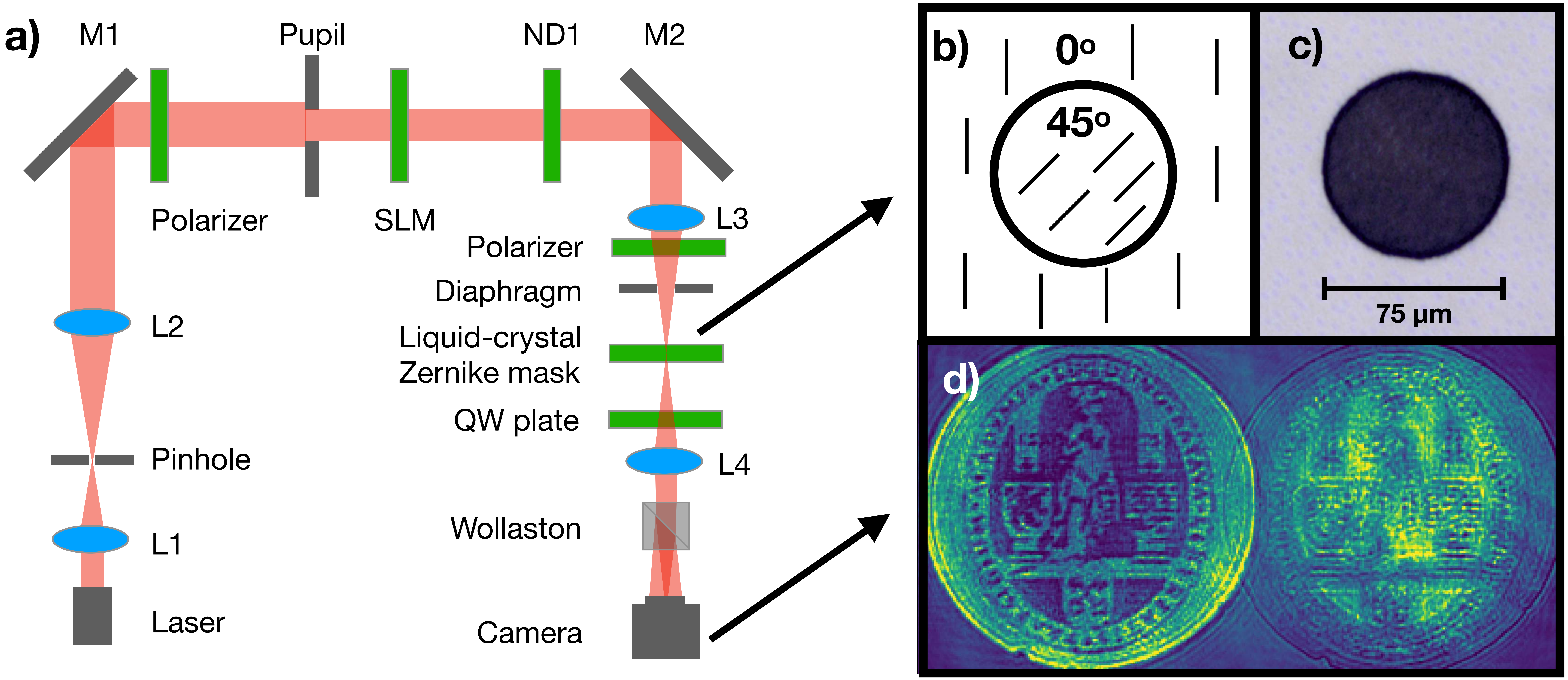
docs.hcipy.org

Manufacturing of the vZWFS

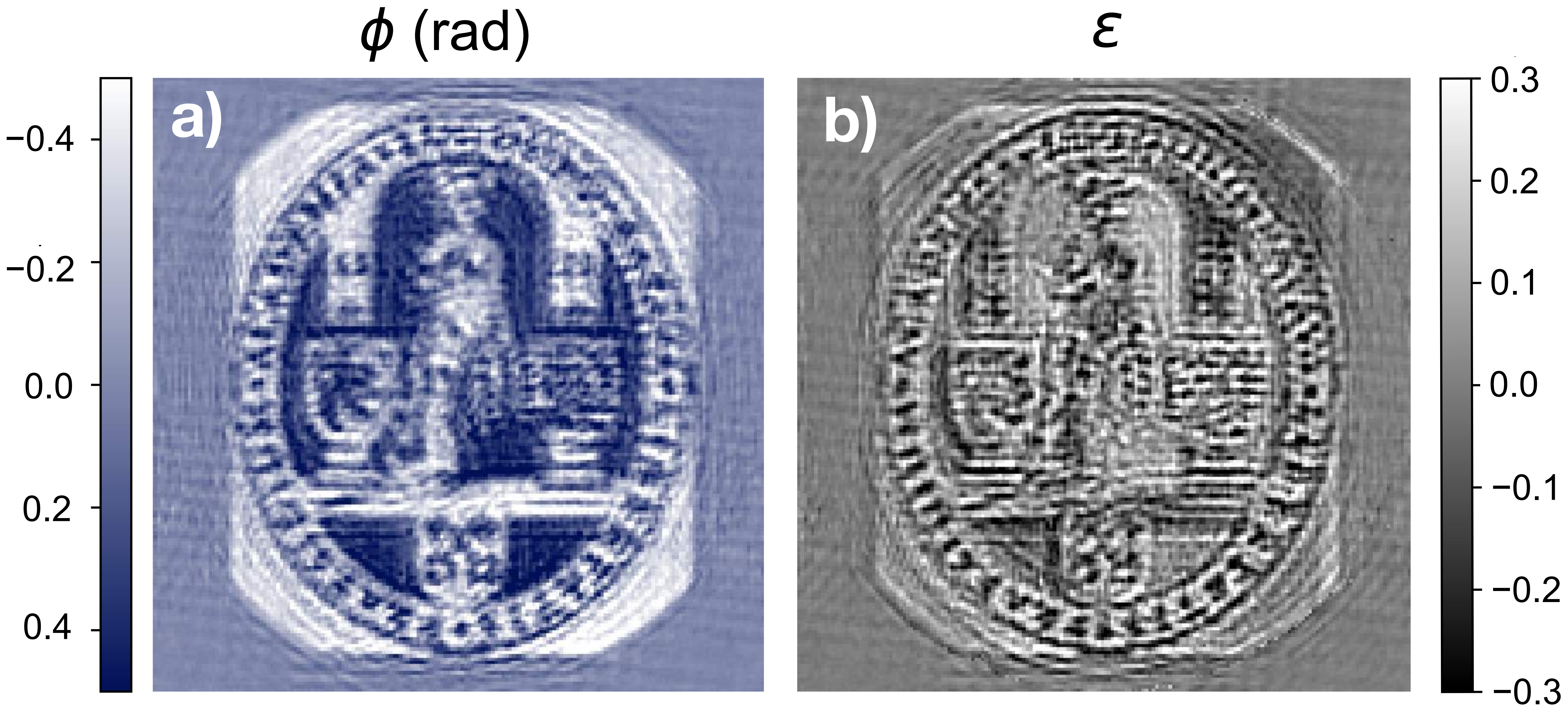
- Manufacturing by the “Geometric Phase Lab” at the North Carolina State University, in collaboration with ImagineOptix
- Manufactured three vZWFS on the same substrate, each with a differently sized dot (30, 50, 70 micron)
- Single non-twisted liquid-crystal layer with a retardance that is half-wave at 633 nm



Lab demonstration

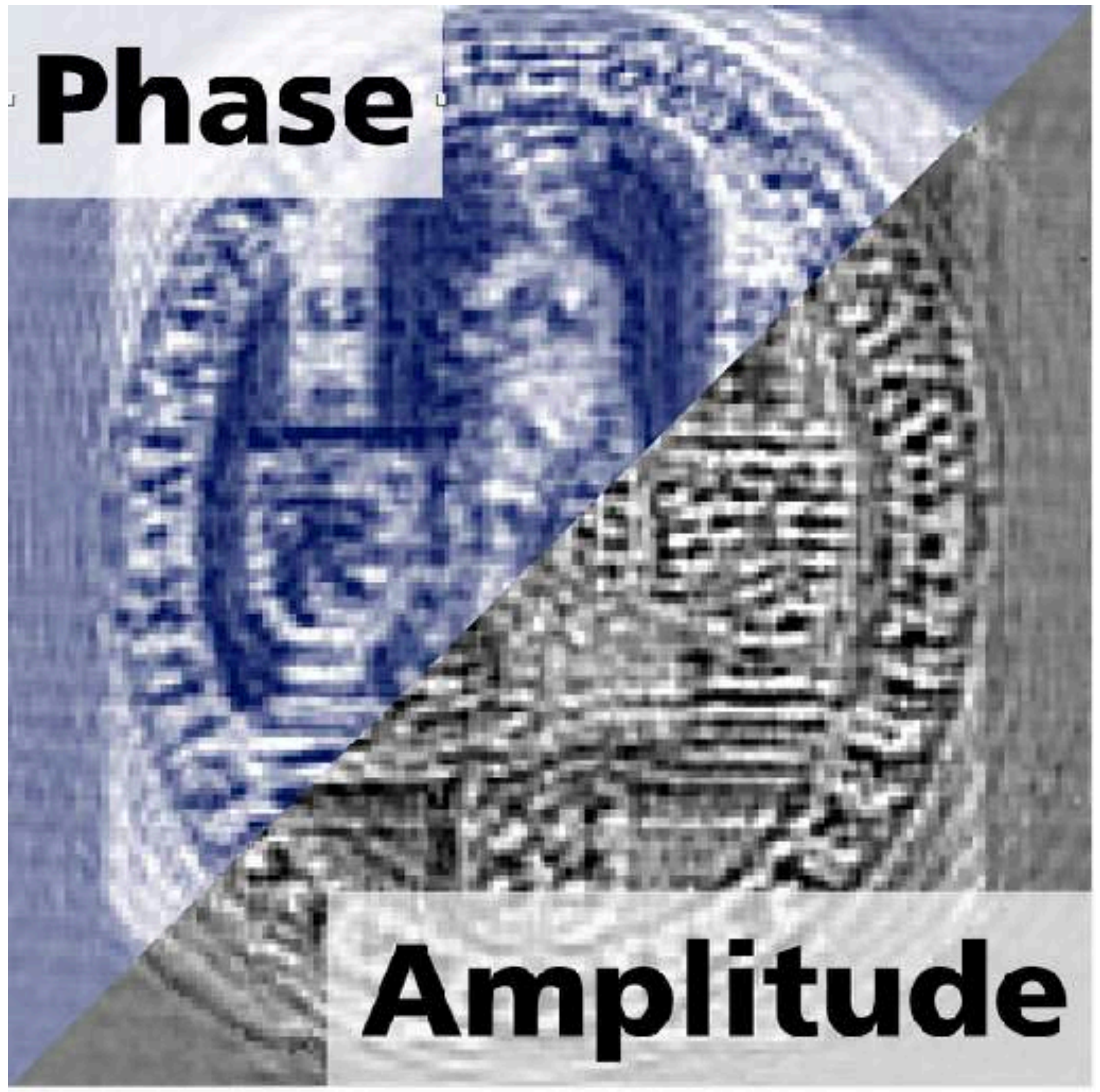


Lab demonstration



Conclusions

- The liquid-crystal vector-Zernike wavefront sensor is a simple yet powerful upgrade of the classical ZWFS
- A liquid-crystal Zernike mask applies a -π/2 and π/2 phase offset simultaneously
- By separating circular polarisation states, the vZWFS is capable of measuring phase and amplitude simultaneously
- The vZWFS has accurate reconstruction over a larger bandwidth than the ZWFS
- The vZWFS is included in the new polarization module of HCIPy.



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Crazy idea

- Add grating pattern to vZWFS phase
- Splits the beam in a $-\pi/2$, $\pi/2$ and 0 (polarization leakage)
- Polarization leakage could be used as absolute reference for the pupil intensity, and solve for b
- Or, depending on retardance, only small amount of light could be split into separate pupils. Most of the light can go into the leakage term, and be used for science
- Downside: the grating smears out the pupil, only small bandwidths possible.