Wavefront Reconstruction for Photonic Adaptive Optics

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Motivation: Reconstruct distorted wavefronts using a photonic integrated circuit in an open loop system.

Introduction

A beam propagating towards Earth is subject to distortions caused by the atmosphere. These random distortions (illustrated in Figure 1) can be corrected with Adaptive Optics (AO). This AO system works by having a Shack Hartmann wavefront sensor (SH-WFS) measure wavefront errors, while the control system uses those measurements to command a phase corrector. A novel photonic corrector is used here that, unlike classical systems, requires sensing the incident wavefront before applying the correction (open loop system).

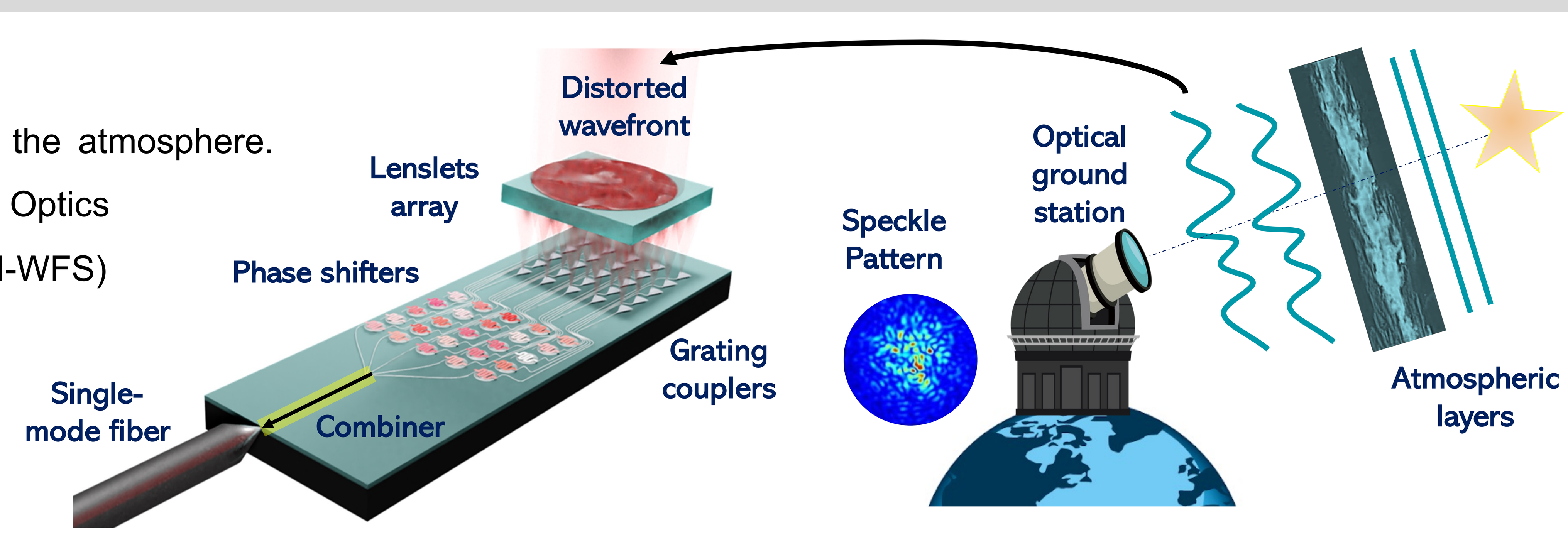

Fig 1. The distorted wavefront arrives at the telescope and is focused by the lenslet array onto grating couplers connected to waveguides where resistive elements are used to co-phase the propagating modes before combining them into a single-mode fiber, correcting the distortions [1].

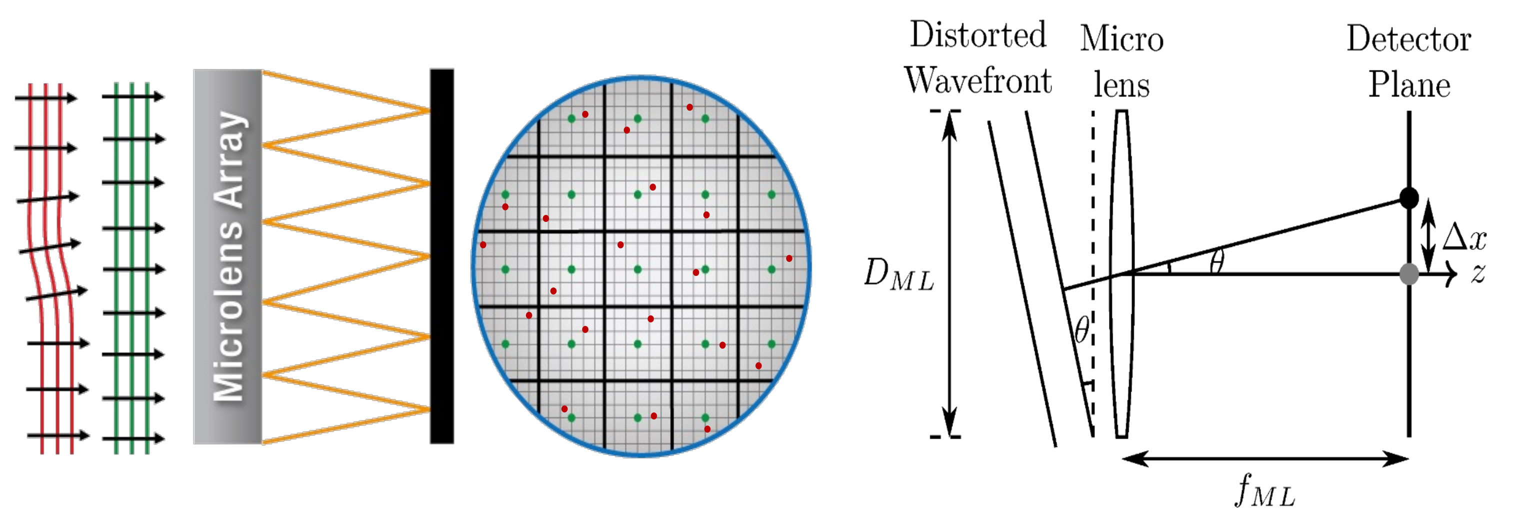

Fig 2. Comparison of a planar (green) and distorted (red) wavefront passing through SH-WFS (left). Geometry of wavefront propagating through a microlens where theta is the wavefront slope (right) [2].

Context

The SH-WFS works by having the beam propagate through an array of positive lenslets that focus the light onto a detector. Through the shifts of the focal spots, as distorted wavefronts propagate, one can calculate the wavefront slopes (Figure 2).

Zernike polynomials are utilized to decompose the wavefronts since Zernike modes are orthogonal on a unit circle. The Zernike modes and wavefront gradients matrix representation are then used to calculate the weight coefficient of each Zernike mode to reconstruct the wavefront.

Methods

The SH-WFS system was constructed as shown in Figure 3. A program was then created to calculate the centroid shifts, wavefront gradients, and weight of each Zernike coefficient. Note that the response of the SH-WFS to the different Zernike modes was calculated from a simulation due to the lack of a deformable mirror in the setup.

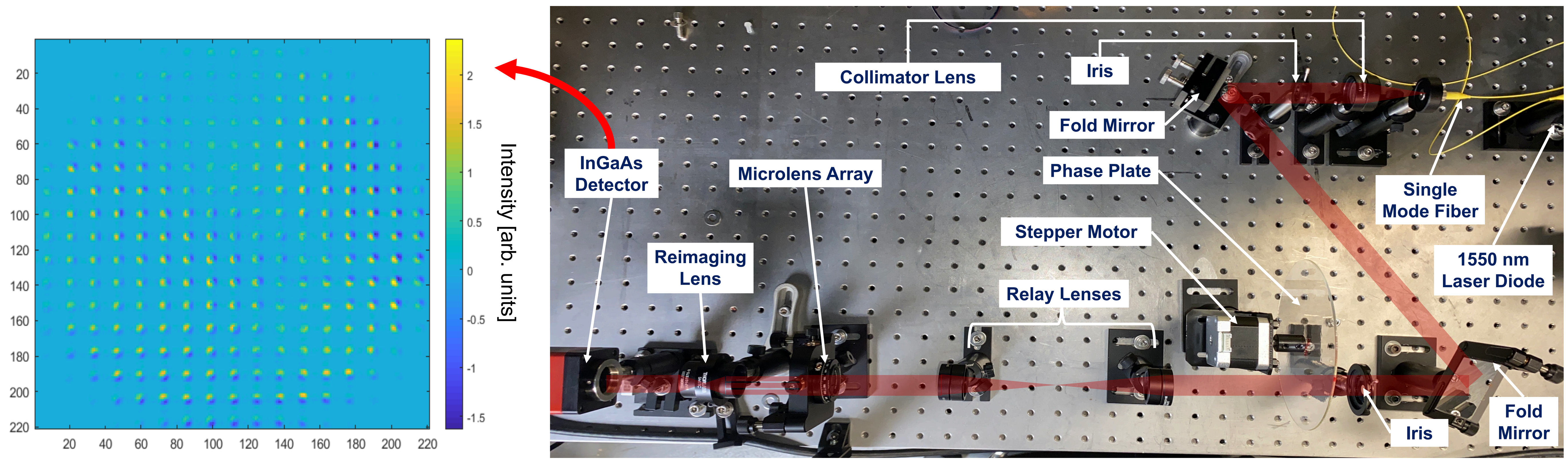

Fig 3. Right: SH-WFS testing optical setup. A fiber-coupled laser is collimated by a lens, a phase screen that introduces atmospheric-like distortion is placed in the pupil plane, and two relay lenses are then used to image the phase screen on the MLA. A 1:1 lens system images the focal spots created by the MLA on the InGaAs detector. Left: Image of focal spots of the wavefront distorted on the detector after subtracting the reference (undistorted) image.

Results

Figures 6 and 7 show the shifts of the focal spots in x and y for one distorted wavefront, while Figure 8 depicts the weight of the Zernike coefficients for each mode. As expected, the low-order Zernike modes, such as those shown in the figure, had a greater weight compared to the high-order ones.

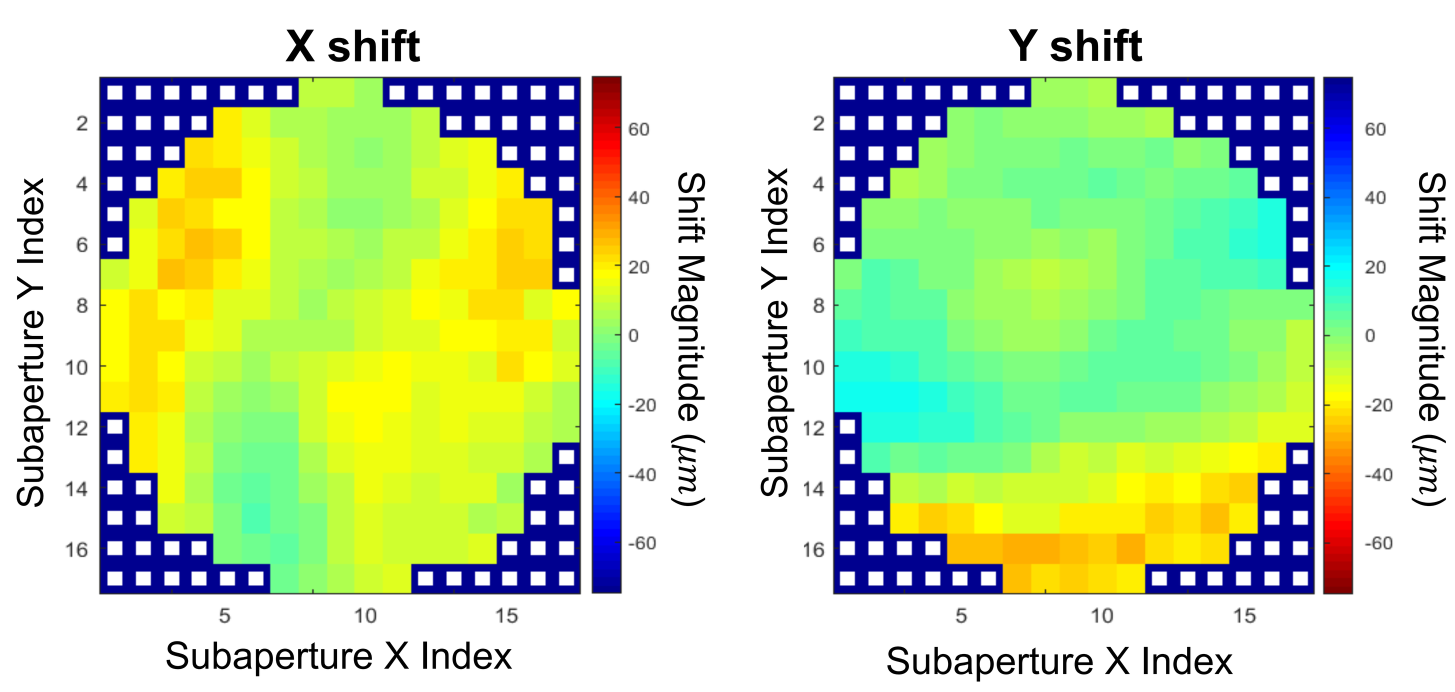

Fig 4. Magnitude of X and Y shifts for each subaperture for a beam diameter of 5.1 mm and a wavefront that has $r_0 = 0.64$ mm.

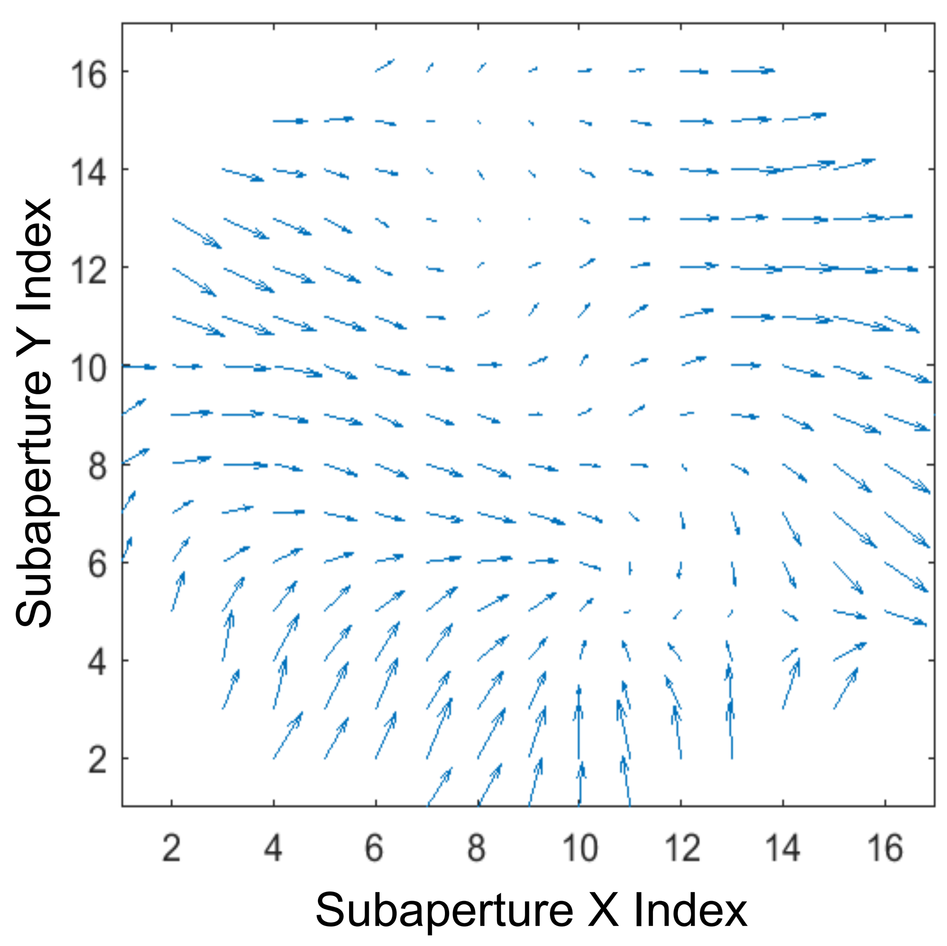

Fig 5. Vector plot of centroid shifts for the same wavefront in Figure 3 and 4.

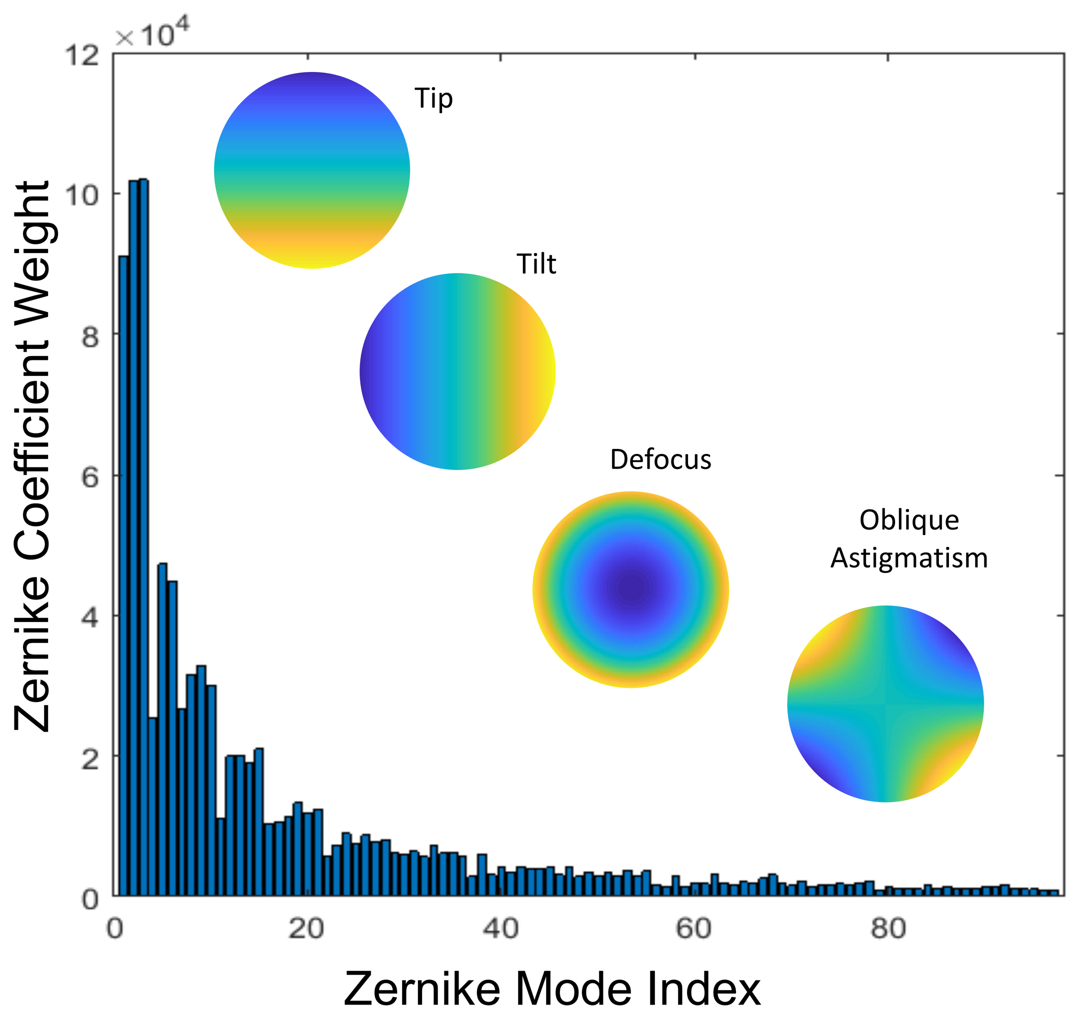

Fig 6. Averaged Zernike coefficients and the first four Zernike modes.

Conclusion and Future Work

With the Zernike coefficients calculated, a method is needed for the photonic chip to work with these measurements to correct the phase distortions. One approach is to simulate the propagation of the Zernike modes through the photonic chip and calculate the phases at each grating coupler as shown below. This combined with the Zernike coefficients measured by the SH-WFS could be used to calculate the commands necessary to correct the distorted wavefront.

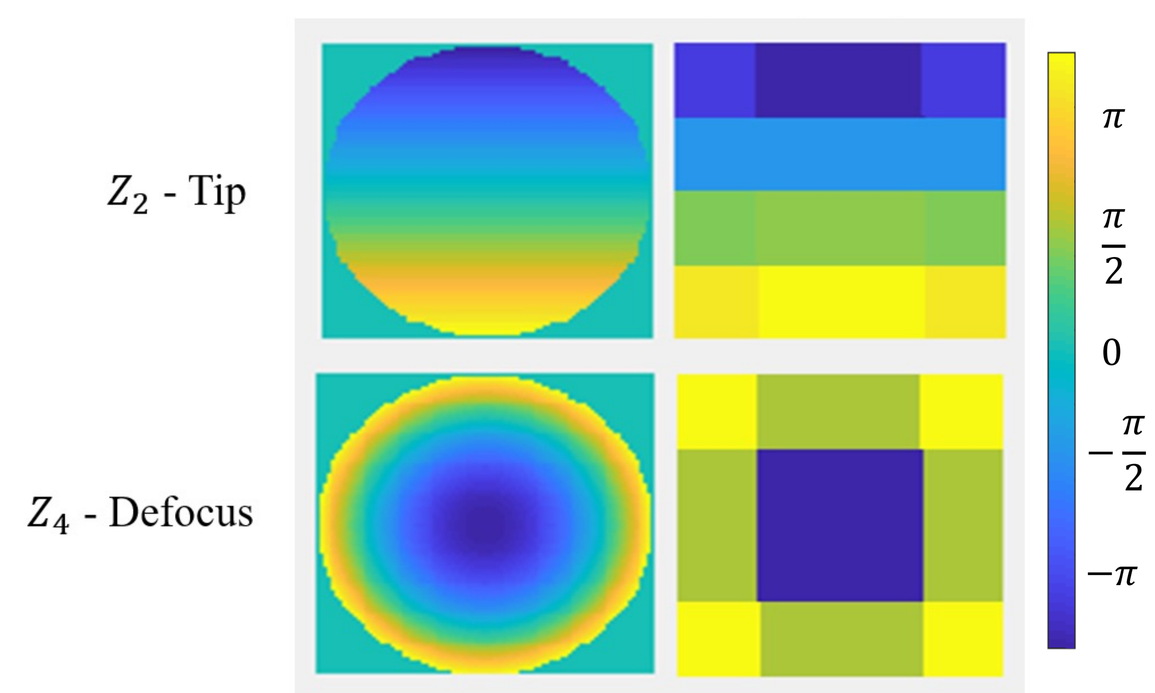

Fig 7. Examples of the photonic corrector response to the second and fourth Zernike modes. The photonic chip simulated here has an array of 4x4 grating couplers.

References

[1] Momen Diab, et al. (2022), 10.1117/12.2642529
[2] Ruurd Kuipers. (2022), Surface Flatness Inspection by Shack-Hartmann Wavefront Sensing.