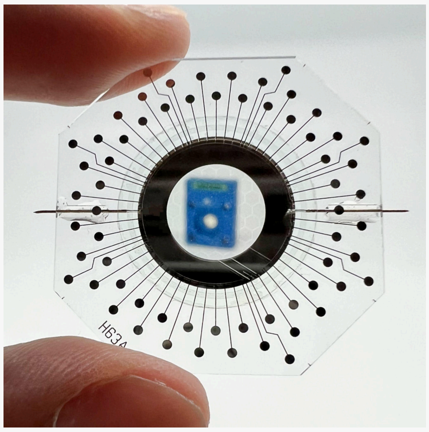
The Deformable Phase Plate Technology

Phaseform develops refractive Adaptive Optics (AO) systems based on innovative hardware and software components. At the heart of our approach to AO is a novel optofluidic microsystem technology called the Deformable Phase Plate (DPP). Its unique features combine the advantages of deformable mirrors and transmissive liquid crystal spatial light modulators in a compact form, paving the way for a new class of ultra-compact, high-efficiency, and transparent wavefront modulators. In this white paper, we describe the main technical pillars of the DPP technology.



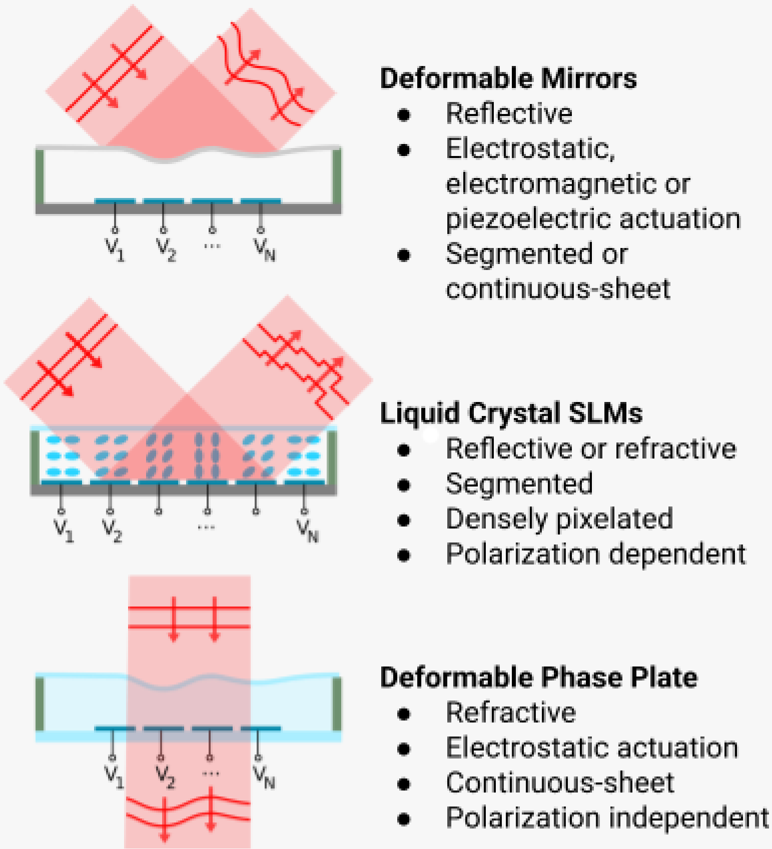


Figure 1: Common wavefront modulators compared with DPP.

Deformable Phase Plate: A new class of wavefront modulator

Wavefront modulators are active devices designed to locally change the optical path length (OPL)—the geometric distance times the refractive index—traveled by light. Two wavefront modulator types dominate the field today:

Deformable Mirrors (DM): These provide high speed, large amplitude, and wavelength- and polarization-independent wavefront modulation. However, their reflective nature can introduce disadvantages in system size, complexity, and cost.

Liquid Crystal Spatial Light Modulators (LC-SLM): These use densely packed liquid crystal cells to locally modify the OPL. They offer very high spatial resolution and can reproduce discrete phase jumps. However, they often suffer from diffraction losses. Furthermore, because their phase modulation is tied to polarization modulation, one polarization component must usually be filtered out to achieve pure phase modulation, leading to significant light loss [1]. Phaseform's **Deformable Phase Plate** (DPP) is a new kind of fully transmissive, miniaturized wavefront modulator. It delivers dynamic, real-time aberration correction and can be placed directly into an optical beam path, much like a regular lens. The key technical features of the DPP include:

- **Transmissive**: Works in refraction, is polarization-independent, and is transparent. This enables new types of continuous-sheet wavefront modulators that can be inserted into the optical beam path without requiring folding optics.
- **Compact**: Exceptionally small form factors enable very compact system designs.
- **High Resolution:** A two-dimensional array of transparent electrostatic actuators is distributed within the optical aperture, offering high spatial frequency correction (including spherical aberrations) with a stroke of multiple visible wavelengths.
- **Scalable**: Wafer-level manufacturing, optofluidic encapsulation, and high-precision assembly result in a robust and scalable technology.

Technology and fabrication

The DPP consists of a sealed, liquid-filled volume with a flexible polymeric membrane on one side and a rigid, transparent glass substrate on the other. An array of individually addressable transparent electrodes, located on the glass substrate, covers the clear pupil. The flexible membrane is supported by a micro-machined spacer, and the enclosed volume is filled with a high-refractive-index liquid.

When a voltage is applied to the electrodes, the conductive membrane is pulled toward the substrate. This motion displaces the liquid, changing the effective optical path length of the light that passes through the wavefront modulator [2]. The total thickness of the DPP is less than 1 mm. This very slim design yields two advantages:

1. Virtually no dispersion (e.g., wavelength-independent behavior).
2. Ability to stack multiple devices in close proximity [3], particularly relevant for emerging AO techniques such as multi-conjugate adaptive optics [4].

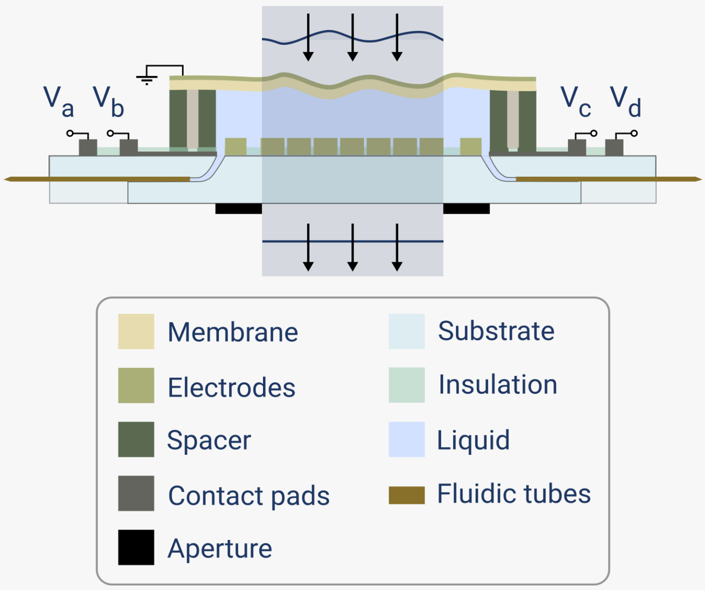


Figure 3: The internal structure of the DPP.

Driving and control

Driving the DPP actuators requires a multi-channel high-voltage amplifier (up to 300 V, depending on device design). Thanks to the low power consumption of electrostatic actuators, standard MEMS driver arrays typically suffice.

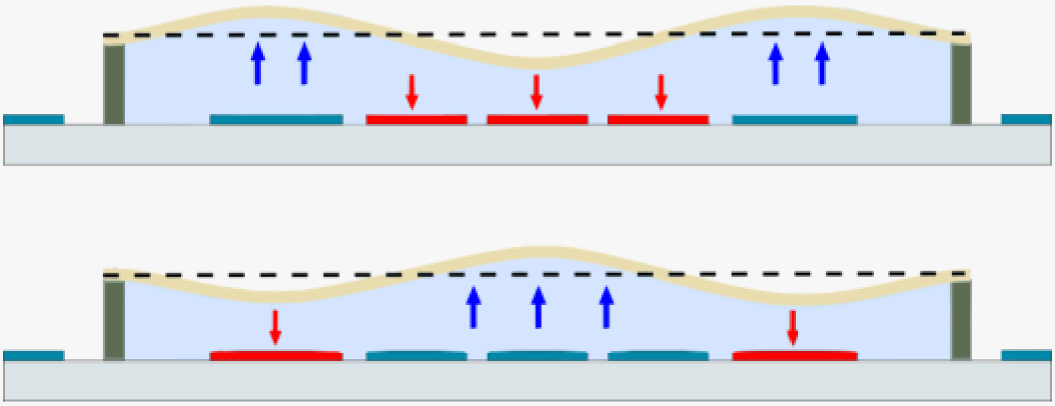


Figure 4: Thanks to the incompressibility of the optical liquid, the DPP is able to achieve push-pull actuation within the clear pupil.

A custom-developed control algorithm, based on well-known constrained optimization methods, calculates the necessary voltages for any given target surface shape in real time [5]. Electrostatic actuation is common in commercial microsystems for its low power consumption, negligible hysteresis, minimal dimensions, and structural simplicity - advantages also seen in the DPP. Although electrostatic actuators only generate an attractive force, the hydro-mechanical coupling between the membrane and the sealed, incompressible liquid allows bidirectional (push-pull) operation [6]. To harness this capability, the DPP includes multiple radial electrodes around the optical aperture that can produce large upward membrane displacements. In contrast to other electrostatic membrane devices, the DPP can be biased around its static position, rather than operating with a constant offset.

High spatial frequency wavefront correction

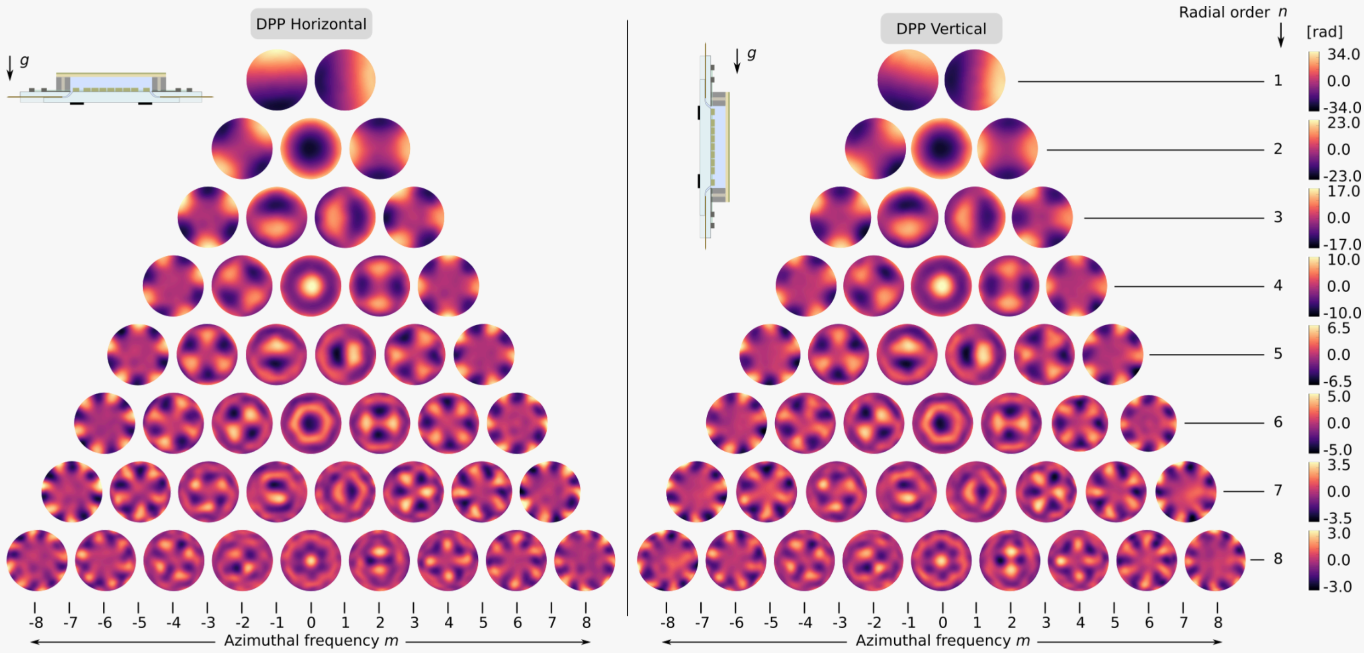


Figure 5: DPP can replicate Zernike modes up to the 7th radial order in open-loop, both in horizontal and vertical orientations. Note the fidelity and amplitude of the first and second-order spherical modes, which are essential in numerous imaging scenarios.

With most of its electrodes located within the clear pupil, Phaseform's DPP offers the versatility of continuous-sheet deformable mirrors in a transmissive, compact, and high-efficiency design. For instance, a 63-actuator DPP can correct up to the 7th radial order of Zernike modes, and the maximum correction amplitude at higher orders still exceeds one visible wavelength. Large amplitudes in first- and second-order spherical aberrations are especially valuable for microscopy.

Optofluidic devices can be sensitive to gravitational effects, which induce a pressure gradient in the fluid chamber. If the optical axis is not parallel to the gravitational force, spurious aberrations can arise. The mechanical design of the DPP, however, keeps gravity-induced aberrations small enough to be corrected without compromising the available range for actual wavefront adjustment. Figure 5 shows the DPP's Zernike-mode replication in horizontal and vertical orientations. Because those spurious aberrations are limited to a small fraction of a wavelength, the device's performance is virtually unaffected by orientation [7].

Cascading multiple DPPs

The DPP's exceptionally low axial thickness and high transmission efficiency enable multiple DPPs to be cascaded in series for enhanced corrective range and fidelity. Figure 6 illustrates an example setup in which two Phaseform Delta 7 devices are stacked in a single optical path. By engineering each DPP to address a different set of aberrations, one can build a "composite" modulator with custom performance characteristics. Figure 7 shows the performance of such a stack: similar to a high-fidelity loudspeaker system with a woofer and tweeter, one DPP is tuned for low spatial frequency aberrations and the other for high-frequency correction [3].

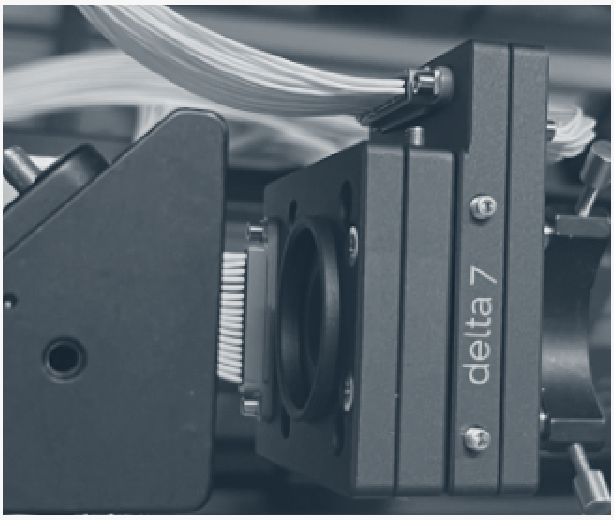


Figure 6: Cascaded DPPs in the form of two stacked Delta 7.

An optimization-based control scheme drives both DPPs simultaneously, correcting a wide range of wavefront aberrations. Compared to a single-modulator arrangement, the cascaded approach significantly expands both the available stroke and the fidelity of wavefront correction for low- and high-order modes.

Multiple-wavefront-modulator (multi-DM) approaches have long been studied, particularly for samples with aberrations arising at various depths. However, practical systems have been rare, mainly due to the complexity of arranging multiple deformable mirrors at separate conjugate planes relayed through additional optics. The DPP's ease of stacking and minimal dispersion make it well-suited to push these new multi-conjugate adaptive optics techniques toward real-world applications.

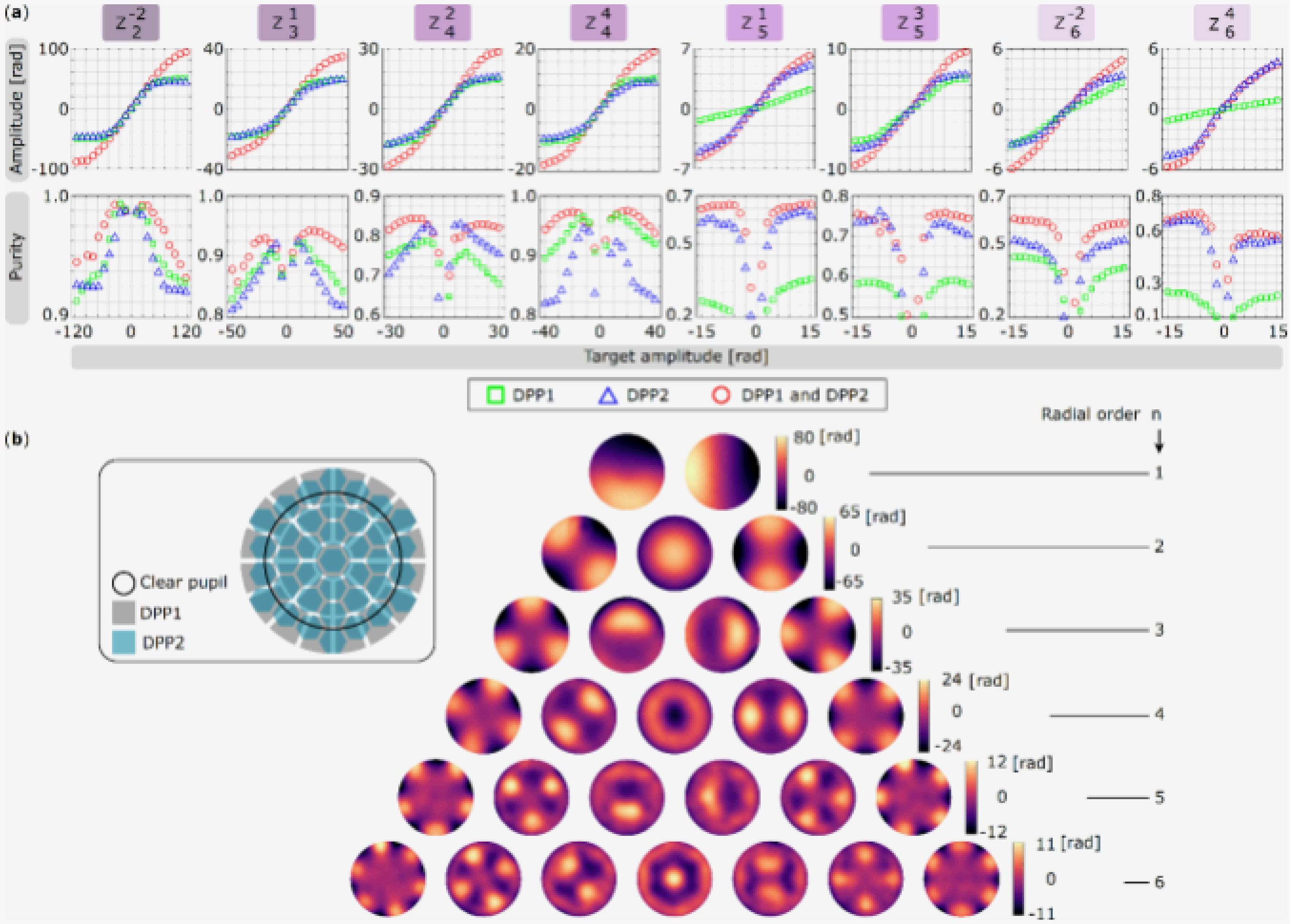


Figure 7: Experimental results for replicating up to the 6th radial order of Zernike modes using two cascaded DPPs with 25 and 37 electrodes, respectively. (a) Comparing the maximum achievable mode amplitude and their corresponding purity using DPP1 and DPP2 individually (depicted by green squares and blue triangles, respectively), and simultaneously with the cascaded configuration and the proposed control method (red circles). (b) Overview of the replicated Zernike modes using the cascaded DPPs. The top-left figure shows the electrode patterns of the two DPPs overlaid on each other [3].

Conclusion

As optical systems grow more powerful and complex, the effects of aberrations on performance become ever more critical. DPP technology provides dynamic reshaping of the wavefront in otherwise static optical systems and ensures optimal performance across diverse scenarios. These new wavefront modulators and adaptive optics solutions, enabled by the DPP, promise to be integral to the next generation of advanced optical systems.

DPP as a General-Use Wavefront Modulator

The first commercial product to incorporate a DPP is the Phaseform Delta 7 wavefront modulator. This continuous-sheet, refractive, optofluidic device features a 63-electrode DPP capable of reproducing Zernike modes up to the 7th radial order. It is compatible with standard optical cage systems and comes with dedicated control software and driving electronics.

Delta 7 Transmissive Wavefront Modulator

The Delta 7 can be used in the fields of Life Science & Microscopy [4,8-12], Vision Science & Ophthalmology [13,14], Material Science & Semiconductors, 3D Micro and Nano Printing, AR/VR/MR and Amateur Astronomy.

About the company

Phaseform GmbH is a deep-tech spin-off from the Department of Microsystems Engineering (IMTEK) at the University of Freiburg in Germany. Our mission is to make adaptive optics affordable and practical by translating decades of cutting-edge research into innovative products and technologies. Phaseform aspires to lead the adaptive optics market with a vision of continuous innovation in a “New Era of Adaptive Optics.”

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References

1. K. Hampson, Adaptive optics correctors. In Handbook of Adaptive Optics. CRC Press, 2024. pp. 20–37.
2. K. Banerjee et al., "Optofluidic adaptive optics," Applied Optics 57.22 (2018): 6338–6344.
3. P. Rajaeipour et al., "Cascading optofluidic phase modulators for performance enhancement in refractive adaptive optics," Advanced Photonics 2.6 (2020): 066005-1–10.
4. K. Hampson et al., "Closed-loop multi-conjugate adaptive optics for microscopy," in Adaptive Optics and Wavefront Control for Biological Systems VI. Vol. 11248. International Society for Optics and Photonics, 2020.
5. P. Rajaeipour et al., "Optimization-based real-time open-loop control of an optofluidic refractive phase modulator," Applied Optics 58.4 (2019): 1064–1069.
6. K. Banerjee et al., "Refractive optofluidic wavefront modulator with electrostatic push-pull actuation," in Adaptive Optics and Wavefront Control for Biological Systems V. Vol. 10886. International Society for Optics and Photonics, 2019.
7. P. Rajaeipour et al., "Seventh-order wavefront modulation with a gravity-neutral optofluidic deformable phase plate," Journal of Optical Microsystems 1.3 (2021): 034502.
8. P. Rajaeipour et al., "Fully refractive adaptive optics fluorescence microscope using an optofluidic wavefront modulator," Optics Express 28.7 (2020): 9944–9956.
9. M. Shomhen et al., "Optofluidic adaptive optics in multi-photon microscopy," Biomedical Optics Express 14.4 (2023): 1562–1578.
10. A. Dorn et al., "Plug-and-play adaptive optics microscopy with full-field correction using isoplanatic patch estimation and field segmentation," Optics Express 32.23 (2024): 41764–41775.
11. A. Dorn et al., "Conjugate adaptive optics extension for commercial microscopes," Advanced Photonics Nexus 3.5 (2024): 056018-056018.
12. J. D. Muñoz-Bolaños et al., "Confocal Raman Microscopy with Adaptive Optics," ACS Photonics (2024).
13. P. Mece et al., "Woofer-tweeter adaptive optics approach for a compact full-field OCT high-resolution retinal imaging over a large field-of-view," Investigative Ophthalmology & Visual Science 65.7 (2024): 3394–3394.
14. M. Bertrand et al., "Clinical full-field OCT assisted by a plug-and-play woofer-tweeter adaptive optics approach for high-resolution retinal imaging over a large field-of-view," Ophthalmic Technologies XXXIV. SPIE (2024).