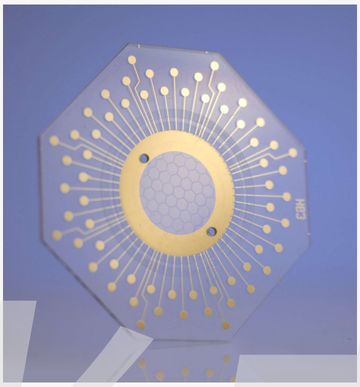
The Deformable Phase Plate Technology

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 that we call Deformable Phase Plate (DPP). Its unique features combine the advantages of deformable mirrors and transmissive liquid crystal spatial light modulators in a compact form, thus paving the way for a new class of ***ultra-compact*****,** ***high-efficiency*****,** ***transparent*** *wavefront modulators. In this article, we describe the main technical pillars of the DPP technology.*



DPP: A new type of wavefront modulator

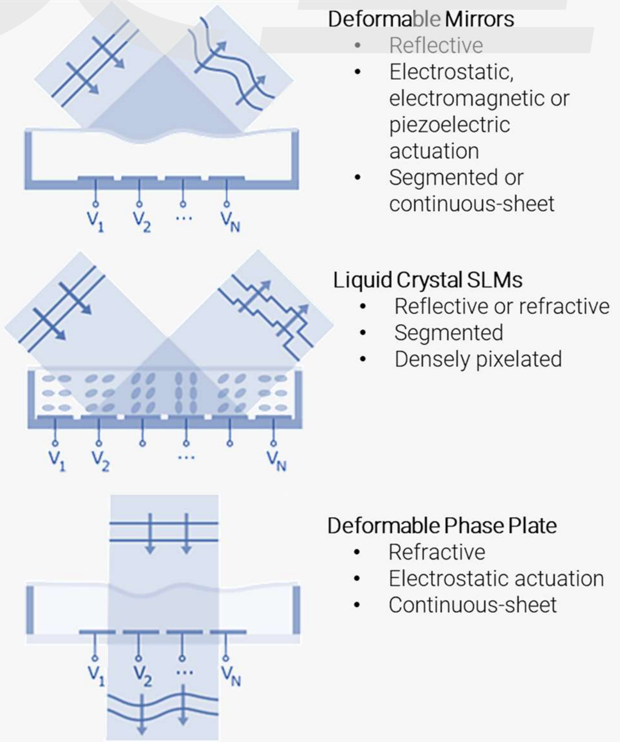


Figure 1: Comparison of common WM types and the DPP

Wavefront Modulators (WM) are active devices designed to locally change the optical path length (OPL: *product of geometric length and refractive index*) traveled by light. There are two popular WM types dominating the field today: Liquid crystal spatial light modulators (LC-SLM) and deformable mirrors (DM). The former use densely packed LC cells to locally modify the OPL. Hence, they have very high spatial resolution, can reproduce discrete phase jumps, but are prone to diffraction losses. Furthermore, the phase modulation is coupled with polarization modulation, and avoiding that is only possible by filtering out a polarization component, which leads to a significant loss of light efficiency.

Deformable Mirrors (DM) offer high-speed, large-amplitude, wavelength and polarization-independent wavefront modulation, essentially addressing the major drawbacks of LC-SLMs. However, for many applications their reflective nature brings disadvantages in system size, complexity, and therefore cost.

The deformable phase plate (DPP) is a new type of completely transmissive, ultra-miniaturized waveform modulator. It can perform dynamic, real-time aberration correction, yet just like a regular lens, can be placed directly into an optical beam path. The key technical features of the DPP technology may be summarized as follows:

- **Transmissive:** The DPP works in refraction. It is polarization-independent and transparent, enabling new types of continuous-sheet wavefront modulators that can be inserted into any optical beam path without beam folding optics.
- **Compact**: Its exceptionally small dimensions allow very compact system designs.
- **High resolution**: DPP offers high spatial frequency correction (including spherical aberration) at a stroke of multiple wavelengths in the visible range.
- **Scalable:** Wafer-level manufacturing, optofluidic encapsulation and high-precision assembly make it a robust and scalable technology.

Scientific origins

The DPP's birthplace is one of the world's leading labs in optofluidics, the Gisela and Erwin Sick Laboratory of Micro-optics in the Department of Microsystems Engineering (IMTEK) at the University of Freiburg in Germany. During the past two decades, researchers there have developed a multitude of active micro-optical components: fluidic lenses, irises, apertures, scanners, aberration-tunable lenses, micro-camera objectives and zoom systems [1]. All this experience is in the DNA of Phaseform's DPP technology.

Figure 2: DPP technology was developed at IMTEK, a world leader in microsystem technology. Image credit: University of Freiburg.

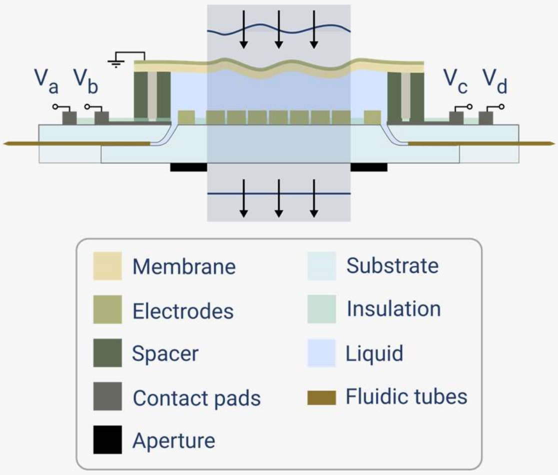


Figure 3: The internal structure of the DPP.

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 on the glass substrate cover the clear pupil area. The flexible membrane is supported by a micro-machined spacer. The volume between the membrane and the substrate is filled with a high-refractive-index liquid. The conductive membrane is pulled towards the substrate when a voltage signal is applied to the electrodes. This actuation displaces the liquid, and changes the effective optical path length of light that refracts through the wavefront modulator [2].

The total thickness of the DPP is only 0.85 mm. This slim design leads to two advantages: Virtually no dispersion (e.g. wavelength independent behavior), and the ability to stack multiple devices in close proximity [3]. This possibility is particularly interesting for emerging AO techniques, such as multi-conjugate adaptive optics [4].

Driving and control

Driving the actuators of the DPP requires a multi-channel high voltage amplifier, with maximum voltage in the range of 250-400 V, depending on the specific device design. Due to the low power consumption of electrostatic actuators, standard MEMS driver arrays are sufficient. A custom-developed control algorithm that uses well-known constrained optimization methods calculates the necessary voltages for any given target surface shape in real-time [5]. Electrostatic actuation is very common in commercial microsystems today; owing this popularity to its **low power consumption**, virtually **non-existent hysteresis**, **minimal dimensions,** and **structural simplicity**. The DPP inherits all these qualities.

Although electrostatic actuators only generates an attractive force, the hydro-mechanical coupling between the membrane and the sealed incompressible liquid can be used for bidirectional (push-pull) operation [6]. To fully exploit this feature, the DPP has a number of radial electrodes circumscribing the optical aperture that can create large upward displacements within the aperture to achieve almost symmetric bidirectional actuation. Therefore, in stark contrast with other electrostatic membrane-type devices, the DPP can be "biased" around its static state, and doesn't operate at an offset.

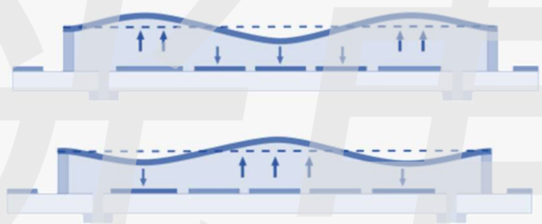


Figure 4: Thanks to the incompressibility of the optical liquid, the DPP is able to achieve push-pull actuation within the clear pupil.

High spatial frequency wavefront correction

With the majority of its electrodes located **within** the clear pupil, the Phaseform DPP offers the versatility of continuous-sheet deformable mirrors in a transmissive, compact and high-efficiency device. For example, a 63-actuator DPP is capable of correcting up to the 7th radial order Zernike modes, and its correction amplitude at the highest order is still greater than two wavelengths in the visible range. The large amplitudes of the first and second order **spherical aberration** modes is particularly important for applications is microscopy.

Optofluidic devices are well-known to be sensitive to gravity effects that deteriorate their performance. This happens due to the pressure gradient induced in the liquid chamber when the optical axis is not parallel to the gravitational force. The mechanical design of the DPP ensures that the spurious gravity-induced aberrations are sufficiently small, such that they can be easily corrected by the device itself without a significant compromise in the available range for actual wavefront correction. The left and right trees of Figure 5 show the Zernike replication performance of the same DPP in horizontal and vertical orientations, respectively. Since the spurious aberrations are limited to coma with an amplitude that is a fraction of a wavelength, the correction performance of the device is virtually unaffected by device orientation.

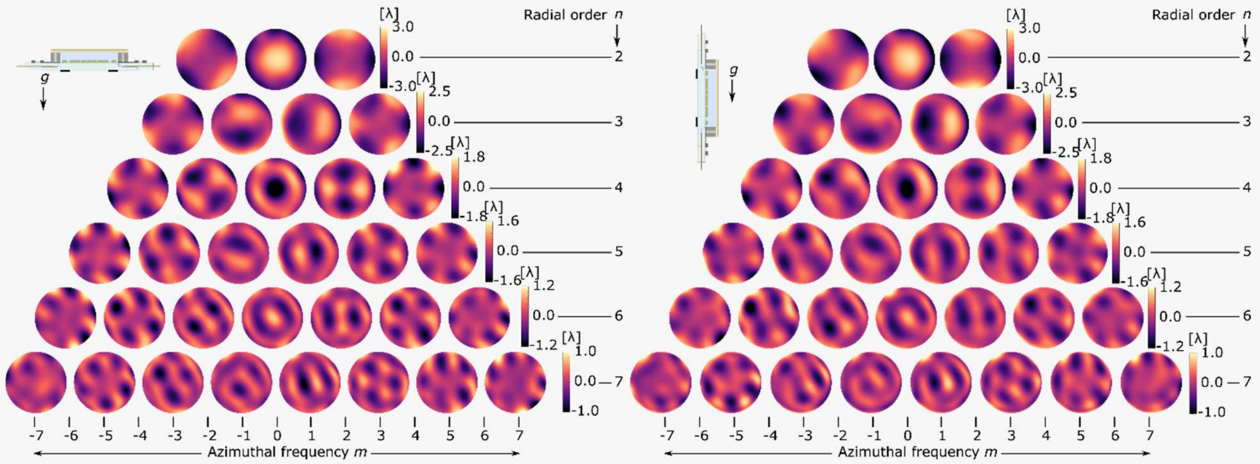


Figure 5: The DPP can replicate Zernike modes up to the 7th radial order in open-loop, both in horizontal and vertical orientations. Optofluidic devices are notoriously sensitive to gravity effects. The DPP overcomes this by a combination of mechanical rigidity and large correction range. Even on the last row, the correction amplitude is larger than two wavelengths in the visible range. This level of articulation is only possible due to the 2D array of transparent actuators covering the optical aperture. Note the fidelity and amplitude of the first and second order spherical modes, which are essential in numerous imaging scenarios.

Cascading multiple DPPs

The exceptionally low thickness along the optical axis and high transmission efficiency makes it possible to cascade multiple DPPs one after another to enhance corrective capabilities, both in range and in fidelity. By engineering multiple cascaded DPPs towards meeting different specific needs of an application, composite modulator units with tailor-made performance characteristics can be developed.

Figure 6 depicts the performance of one such unit. In this configuration, similar to hi-fidelity loudspeakers with separate woofer and tweeter units, one of the DPPs (with 25 electrodes) is optimized for low spatial frequency aberrations, while the second (with 37 electrodes) is used for high-frequency correction [3]. An optimization-based control scheme enables simultaneous operation of both phase modulators for a large range of wavefront aberrations. Compared to the typical single modulator configuration, this arrangement significantly improves the available stroke and wavefront correction fidelity both for low- and high-order modes.

The scientific literature is rich in wavefront correction schemes that require multiple WMs, particularly when target aberrations arise from different depths of the sample. However, practical implementations of these methods have been very few and far between, due to the sheer complexity of using multiple DMs, each located at a different conjugate plane relayed through additional optics. The DPP technology will be instrumental in pushing these new techniques forward into real, practical use.

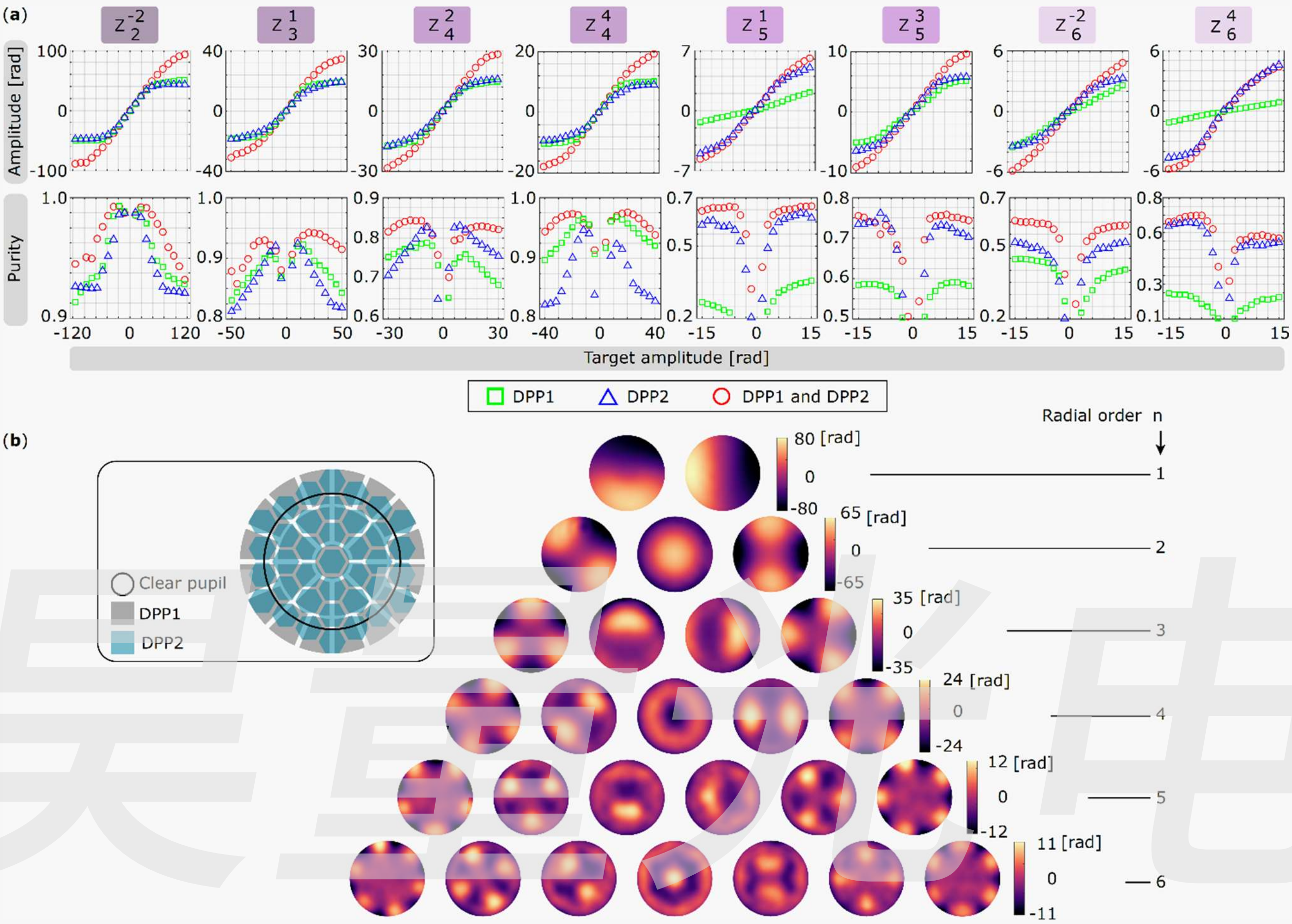


Figure 6: Experimental results for replicating up to the 6th radial order of Zernike modes using two cascaded DPPs with 25 and 37 electrodes, respectively. (a) Comparing the maximum achievable mode amplitude and their corresponding purity using DPP1 and DPP2 individually (depicted by green squares and 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 become more powerful and complex, the impact of optical aberrations on their performance grows in significance. DPP technology delivers dynamic reshaping abilities to static optical systems, and provides the means to ensure optimum system performance under diverse scenarios. We envision that these new breeds of wavefront modulators and adaptive optics systems enabled by the DPP technology will become an essential part of the optics of the future.

DPP as a General-Use Wavefront Modulator

The first implementation of a DPP into a commercial product will be our Phaseform Delta 7 wavefront modulator*. It is a continuous-sheet, refractive, optofluidic wavefront modulator that features a 63-electrode Deformable Phase Plate capable of replicating up to the 7th radial order Zernike modes. It has an aperture diameter of 10 mm, is compatible with 30 mm optical cage systems and comes with dedicated driving electronics and control software. The Delta 7 can be used in the fields of Life Science & Microscopy, Vision Science & Ophthalmology, Material Science & Semiconductors, 3D Micro and Nano Printing, AR/VR/MR and Amateur Astronomy.

*Product preview. All specifications and illustrations subject to change.

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