

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.

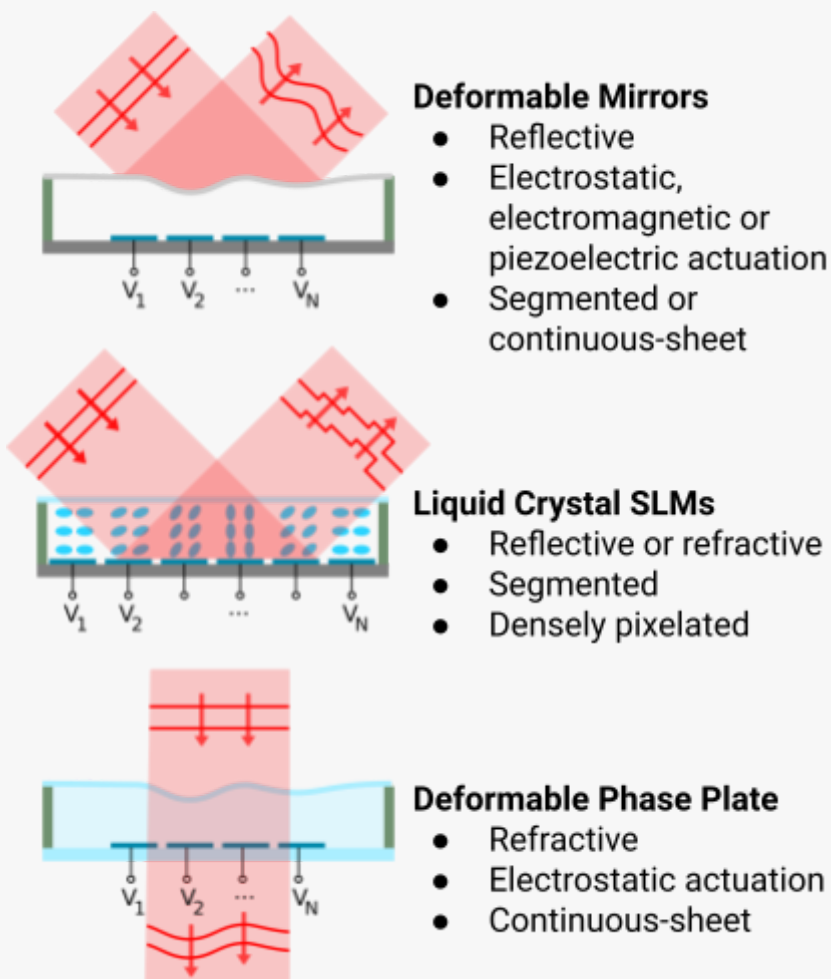
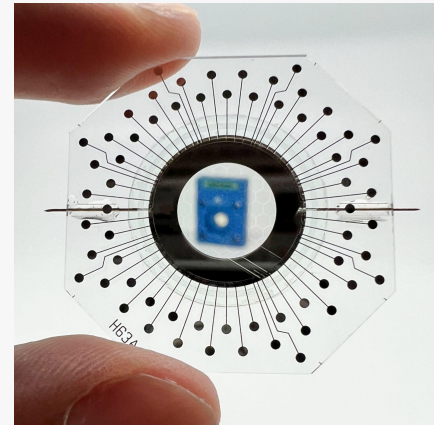


Figure 1: Comparison of common WM types and the DPP

Deformable Phase Plate: A new class of wavefront modulator

Wavefront Modulators (WM) are active devices designed to locally change the optical path length (OPL), the geometric length times refractive index, traveled by light. There are two popular WM types dominating the field today: Deformable mirrors (DM) and Liquid crystal spatial light modulators (LC-SLM).

Deformable mirrors offer high speed, large amplitude, wavelength and polarization independent wavefront modulation. However, for many applications their reflective nature brings disadvantages in system size, complexity, and therefore cost.

LC-SLMs use densely packed liquid crystal 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 one polarization component, which leads to a significant loss of light efficiency.

Phaseform's Deformable Phase Plate (DPP) is a new type of completely transmissive, 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.

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 less than 1 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] which is particularly interesting for emerging AO techniques, such as multi-conjugate adaptive optics [4].

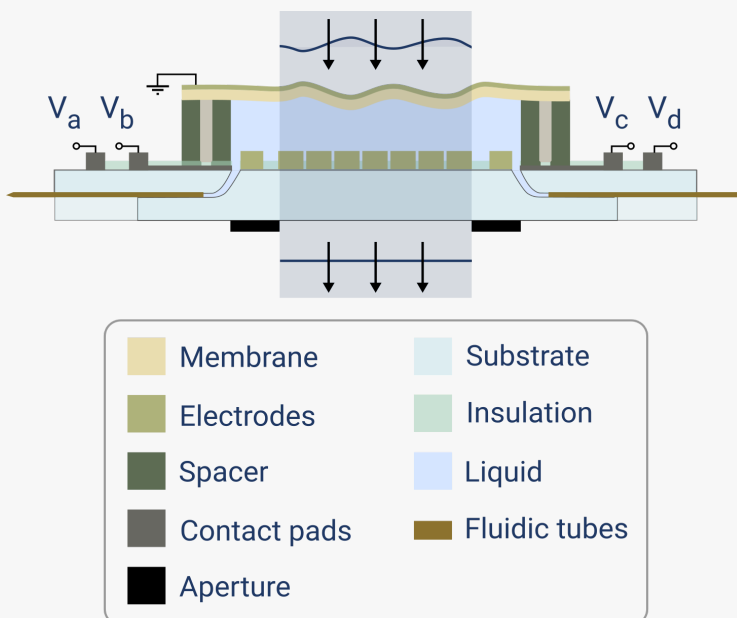


Figure 3: The internal structure of the DPP.

Driving and control

Driving the actuators of the DPP requires a multi-channel high voltage amplifier, with maximum voltage up to 300 V, depending on the specific device design. Due to the low power consumption of electrostatic actuators, standard MEMS driver arrays are sufficient.

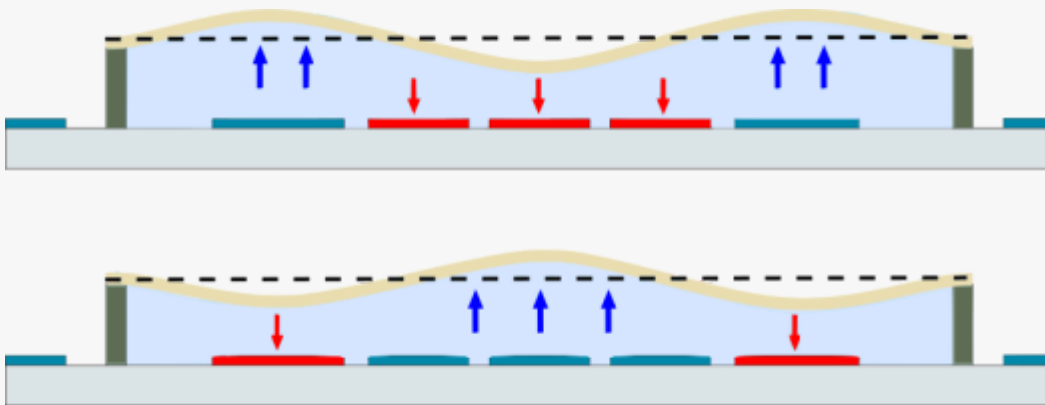


Figure 4: Thanks to the incompressibility of the optical liquid, the DPP is able to achieve push-pull actuation within the clear pupil.

A custom-developed control algorithm 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 - qualities which the DPP inherits. Although electrostatic actuators only generate 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.

High spatial frequency wavefront correction

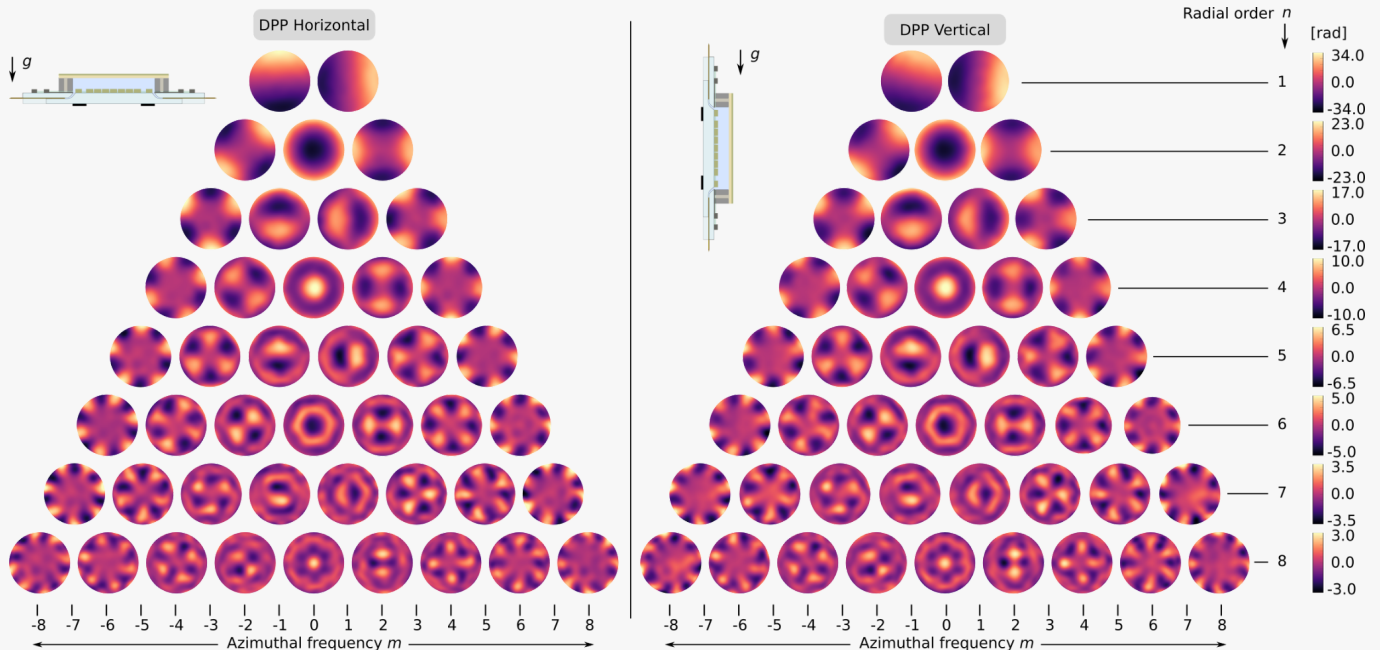


Figure 5: DPP can replicate Zernike modes up to the 7th radial order in open-loop, both in horizontal and vertical orientations. Note the fidelity and amplitude of the first and second order spherical modes, which are essential in numerous imaging scenarios.

With 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 are particularly important for applications in 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 [7].

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. Figure 6 shows an example for stacking two of Phaseform's Delta 7 devices in an optical path. 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 7 depicts the performance of one such unit. In this configuration, similar to hi-fidelity loudspeakers with separate woofer and tweeter units, one DPPs is optimized for low spatial frequency aberrations, while the second is used for high-frequency correction [3].

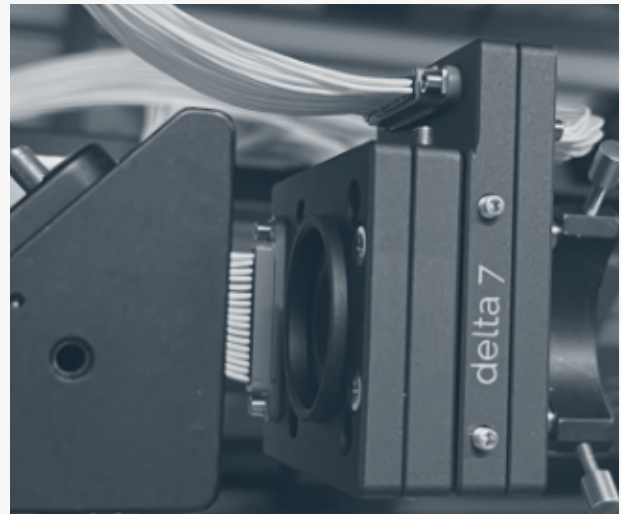


Figure 6: Cascaded DPPs in the form of two stacked Delta 7.

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.

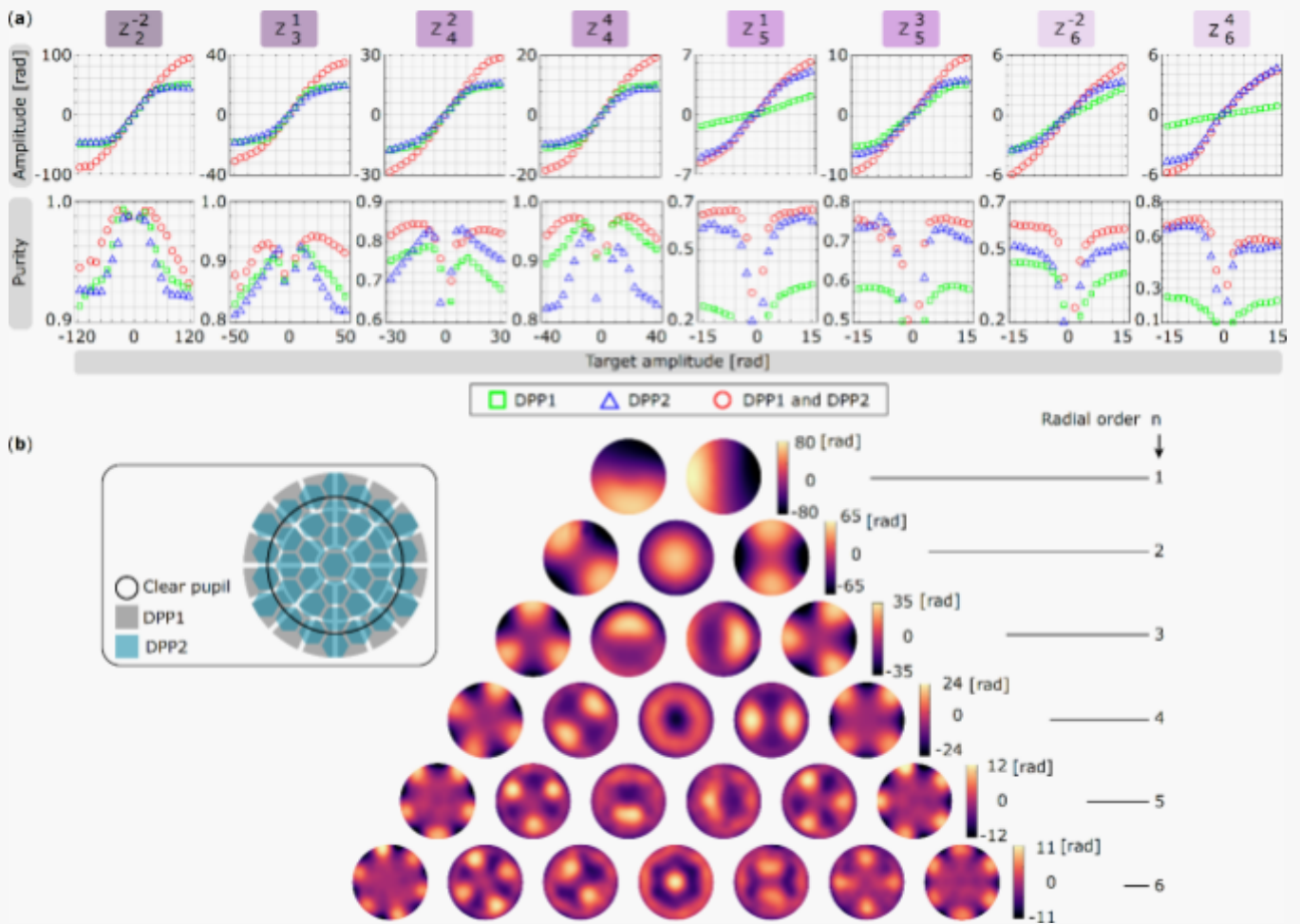


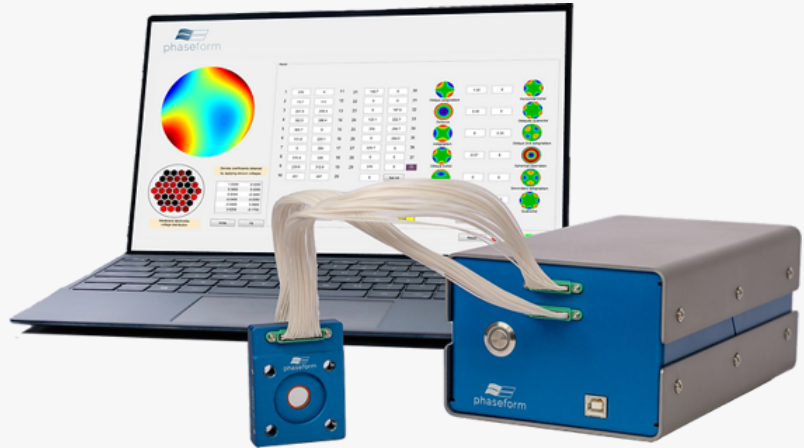
Figure 7: Experimental results for replicating up to the 6th radial order of Zernike modes using two cascaded DPPs with 25 and 37 electrodes, respectively. (a) Comparing the maximum achievable mode amplitude and their corresponding purity using DPP1 and DPP2 individually (depicted by green squares and 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 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 is the **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 of 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.



*Phaseform Delta 7 product preview.
Specifications subject to change.

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.

About the company

Phaseform GmbH is a deep-tech spin-off from the Department of Microsystems Engineering (IMTEK) of the University of Freiburg in Germany.

Our goal is to make Adaptive Optics affordable and practical, and to bring decades long cutting-edge research into fruition with innovative products and technologies. Phaseform aspires to become a leading adaptive optics technology company with a clear vision of continuous innovation in a “New Era of Adaptive Optics”.

Phaseform GmbH

Georges-Köhler-Allee 102
79110 Freiburg i.B., Germany

Email: info@phaseform.com

Web: www.phaseform.com

Phone: +49 761 6007 9018

References

1. <https://www.imtek.de/laboratories/micro-optics/publications>
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." *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." *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.