Deformable mirror with increased correction capabilities

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A miniature deformable mirror with optional dielectric coating for high laser power handling enables high-order aberration correction and the creation of phased arrays and optical vortices.

Researchers have employed adaptive optics (AO), a technology that corrects for optical aberrations, to dramatically improve image quality when the medium between the object and the imaging sensor creates optical path differences that vary spatially and/or temporally. Although AO was originally applied to defense and astronomy, in the past decade researchers have used the technology for retinal imaging,\(^1\) microscopy,\(^2\) and laser micromachining.\(^3\)

One of the enabling components in an AO system is a deformable mirror (DM). The DM changes its shape to correct for aberrations that degrade imaging performance. For practical high-performance systems, the DM aperture should match the application at hand. Further, it should have adequate spatial fidelity. Microscopy and retinal imaging require DM apertures of 3–10mm with up to hundreds of actuators to shape the mirror surface.

Iris AO has been developing DMs since 2002. From the start, the focus has been on building high-stroke DMs that are easy to operate, robust to environmental conditions, and capable of precision open-loop operation. We employ microelectromechanical systems (MEMS) technology to fabricate compact, high-actuator-count DMs. Figure 1 shows our most recently developed DM, the PTT489.\(^4\) It has 489 actuators with 163 piston/tip/tilt (PTT) segments capable of a >9\(\mu\)m stroke. The mirror surface consists of a tightly packed hexagonal array of three-degrees-of-freedom hexagonal segments. The DM can be shaped to create smooth surfaces in a piecewise linear fashion. Because there is no mechanical coupling between the segments, stepped surfaces such as phased arrays can be created as well. Figure 2 shows an example of the shapes that such a DM can create. The tremendous flexibility afforded by the segmentation has allowed our DMs to be used not only in traditional AO applications such as retinal imaging,\(^5\) but also for creating optical vortices,\(^6\) coherently combining beams in a multi-core fiber,\(^7\) and implementing novel AO schemes that also require independent PTT segment control.\(^8\)

The foundation of our MEMS DM technology is the mirror segment shown in Figure 3. Segments are positioned by applying the appropriate drive voltages to the three diamond-shaped electrodes that lie under the actuator platform. As part of the MEMS fabrication process, arrays of the relatively thick mirror segments (25–50\(\mu\)m) are flip-chip bonded onto actuator arrays.\(^9\) The rigid segments result in flat surfaces that are stable over large operating temperatures.

Our DMs are factory calibrated to provide precision open-loop operation using intuitive PTT commands for each segment. The calibrated position controller linearizes the relationship between the desired PTT positions and the requisite drive voltages for the underlying actuator electrodes.\(^10\) The combination of flat mirror segments and precision open-loop control has resulted in nicely formed point-spread functions (see Figure 4). Only when the camera is highly saturated do diffraction effects become apparent.\(^11\) Hence, the segmented DMs are suited to demanding imaging applications.

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The segmented DM design with its precision linear open-loop operation has many advantages when used in a closed-loop AO system. When the DM and wavefront sensor (WFS) are optimally matched and aligned, the control matrix is diagonal with no cross terms from neighboring actuators. All that is required for AO systems with our segmented DMs is a simple alignment between the DM and the WFS. Other systems rely on more complex influence functions to map the Shack-Hartmann WFS measurements to the DM control voltages. The diagonalized control matrix reduces the computation time and is trivial to parallelize for large arrays. An example is AO retinal imaging systems. State-of-the-art research systems typically update at 10–15Hz. Our off-the-shelf PTT111-based systems update at 60Hz and have produced imaging on par with other research-grade AO retinal systems despite correcting with only 37 PTT segments (111 actuators).

We recently demonstrated DMs with high-reflectance dielectric coatings (R > 99.85%) centered at 532, 1064, and 1540nm. The mechanically rigid segments in Figure 3 are ideally suited to the application of these relatively thick coatings. Other MEMS (microelectromechanical systems) approaches that have thinner optical surfaces are prone to large deformations when thick dielectric coatings are used. This development offers unique power handling in a MEMS DM. For the 1064 and 1540nm coatings, the residual surface figure in the segments was < λ/75 rms. Power handling projections based on initial laboratory testing with a 2W 532nm continuous-wave laser showed that off-the-shelf DMs can handle an average power of 300W/cm² with a λ/20 rms increase in surface figure caused by mismatches in thermal expansion between the coatings and the DM. Projections show that with optimized packaging to increase heat flow, the DMs should be able to reach 2.8kW/cm² average power handling.

In summary, we have been developing high-performance MEMS-based deformable mirrors for a decade. Our segmented DMs have demonstrated performance on par with those of continuous facesheet mirrors with similar numbers of actuators. The

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Recent release of the PTT489 DM brings even greater performance and expands the application space for MEMS DMs into the high-power laser arena. These segmented DMs not only meet the needs of demanding AO applications. They also enable new applications that exploit the beam-steering capabilities of the segmented design. Future work to determine the laser damage threshold limits, increase the laser power handling, and build larger mirrors will further expand the application areas for our DMs.

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References