Deformable Mirror Technologies at AOA Xinetics

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ABSTRACT

AOA Xinetics (AOX) has been at the forefront of Deformable Mirror (DM) technology development for over two decades. In this paper the current state of that technology is reviewed and the particular strengths and weaknesses of the various DM architectures are presented. Emphasis is placed on the requirements for DMs applied to the correction of high-energy and high average power lasers. Mirror designs optimized for the correction of typical thermal lensing effects in diode pumped solid-state lasers will be detailed and their capabilities summarized. Passive thermal management techniques that allow long laser run times to be supported will also be discussed.

Keywords: deformable mirrors, adaptive optics, high energy lasers, actuators

1. INTRODUCTION

The concept of traditional DMs is quite simple. A two dimensional array of actuators is bonded to a thin facesheet which forms the optical reflector. Acting against a stiff reaction plate the force of the actuators deflects the facesheet and produces a local deformation of the surface. Since the actuator's force is perpendicular to the mirror surface these DMs are termed Surface Normal. Over the last several years AOX has explored a range of alternative architectures for DMs. The results of this research are presented graphically in Figure 1.

In the upper left of the figure is the conventional surface normal configuration with discrete actuators. Driven by the desired increase the actuator spatial density, AOX has developed the Photonex Mirror Module which incorporates a technique for forming monolithic blocks of actuator material where the individual actuators are defined by saw cuts in the block. These are shown in the lower left of Figure 1 in a surface normal arrangement similar to the Conventional DM.

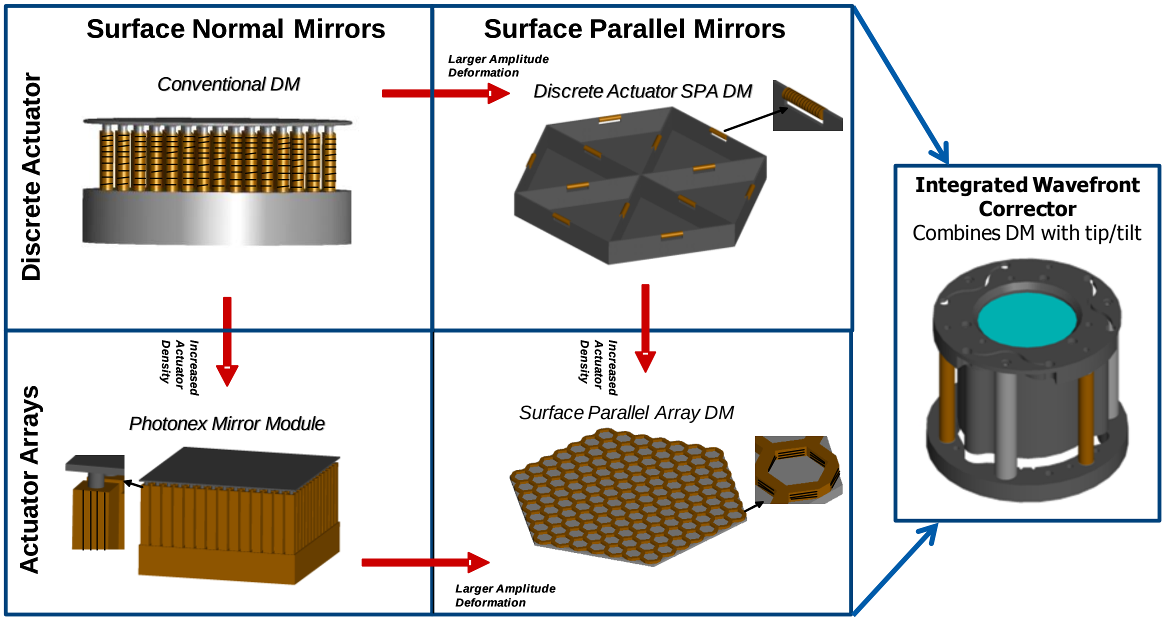


Figure 1. Matrix of Deformable Mirror Architectures

A very different mechanical behavior is obtained if the actuators are placed parallel to the optical surface. A realization of the Surface Parallel Mirror architecture is shown in the upper right of Figure 1. In this case the actuator imparts a bending moment to the structure which leads to a global deformation of the surface. No reaction plate is required since the actuator applied its force to two separated points in a plane parallel to the surface. In this case discrete actuators are bonded into the stiffening ribs of a lightweight mirror structure.

Analogous to the Photonex Mirror Module approach, the Surface Parallel Array (SPA) architecture also has a monolithic version in which the actuators are formed in a micro-machined web that is bonded to the thin mirror facesheet. This is shown in the lower right section of Figure 1.

A strong desire exists to not only decrease the actuator spacing but also compact the optical systems and simplify their operation. Adaptive optics requires that the image plane always be relayed to the active optic to insure that the correction is done purely in phase space. The relay optics needed to insure this cause the systems to increase in size and complexity. AOX has merged the functionality of a steering mirror and DM into a single device to reduce the need for as many relay points. To that end, the Integrated Wavefront Corrector (IWC, shown on the right of Figure 1) incorporates a tilt stage into a deformable mirror thereby combining two functions into a single device. Any of the DM architectures described may be used in the IWC.

In the following sections the characteristics of each of these DM architectures will be discussed.

2. DISCRETE ACTUATOR SURFACE NORMAL DEFORMABLE MIRROR

AOX has preserved critical defense-related active materials technologies by developing commercial precision motion control products. Its first product was a commercial line of deformable mirrors for astronomy, which feature lead magnesium niobate (PMN) electroceramic actuators. Actuator reliability is a key to scaling the mirror technology to the large scale. Our PMN actuated deformable mirror product is driven routinely in the field to $1\text{x}10^{11}$ cycles at stresses and strains comparable to what would be encountered in high speed astronomical adaptive-optics applications.

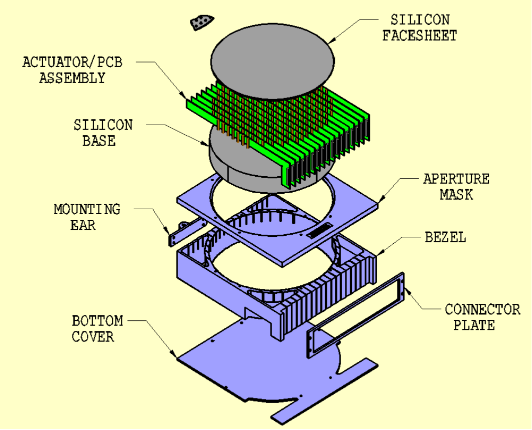


Figure 2. Typical AOX Deformable Mirror Assembly

AOX standard deformable mirror designs utilize a modular assembly approach. This saves time, money, and insures a more reliable product. Figure 2 shows an exploded view of a typical mirror. Its distinguishing feature is the single optical assembly consisting of base, actuators, and facesheet potted inside a metal bezel. The RTV potting prevents thermal distortions of the optical components by absorbing any differential expansion between the metal bezel and optical assembly.

In a higher density design, actuator spacing of 5 mm prevents the use of discrete actuator cards. In this case, machining of the base with individual holes allows the actuator wires to be inserted through the base to the back of the mirror. Here, a single board accepts the actuator wires and relays the signals to individual connectors. These connectors provide the interface to the driver electronics.

2.1 Actuators

The heart of the deformable mirror would be the PNM actuators. All AOX deformable mirrors use our unique PMN multilayer cofired actuator technology. The PMN multilayer actuator fabricated by AOX features low hysteresis, high tensile strength, and nanometer precision-the key to reliable and precise deformable mirror operation. Figure 3 depicts our commercial cofired multilayer actuator stacks that feature operation below 100 volts, tensile strengths in excess of 3500 psi, and strain levels of 1000 ppm.

Figure 3. AOX Deformable Mirror Actuator Assembly

The electroceramic materials feature low hysteresis, low thermal expansion, and high elastic modulus. In terms of energy per active material volume, AOX's PMN electrostrictive formulation is two times greater than cofired piezoelectric lead zirconate titanate (PZT). PZT actuators are unable to meet a variety of requirements for operating in a precision optical system. The silver used in the production of PZT actuators migrates within the actuator eventually shorting the actuator within a few hundred thousand cycles. In addition, the well documented short and long term creep of PZT means that precision and stable figure control is not possible eventually resulting in loss of dynamic range. Production of actuators that can withstand the stress of high cycle operation and can withstand environmental effects such as humidity, shock, and temperature is a key to insuring system performance.

Quality control of AOX PMN actuators insures consistent operation. AOX routinely fabricates actuators with overall actuator stroke uniformity at 100 V of <2.5% with linearity of >99%. The material hysteresis of <1% at room temperature will increase as the mirror approaches -5°C. The hysteresis within this temperature range will be 2.5-20% (see Figure 4).

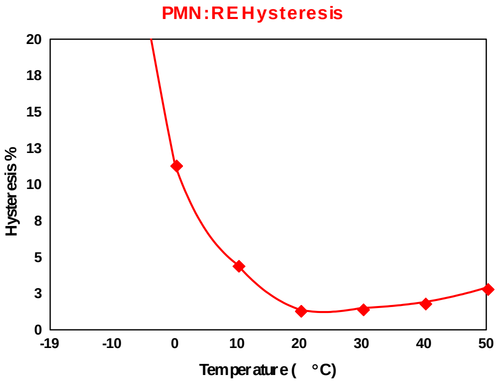


Figure 4. Hysteresis vs. Temperature for PMN

Capacitance of a typical actuator for this application would be 1.8-2 µF. Coupling this with the performance of the AOX driver system would result in a small signal bandwidth of 15 kHz and large signal response of 2 kHz. This is much higher than needed for the requirements of this system.

Figure 5 and Figure 6 show the measured characteristics of the AOX actuators. Over the driver operating range the response is linear with a correlation coefficient greater than 0.99. PMN actuators have a gain change with respect to temperature of 2.7%/deg K. They are specified for operation at 22 deg C.

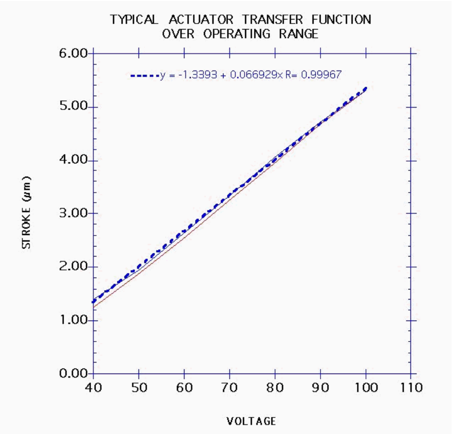


Figure 5. Typical Response Function vs. Operational Voltage

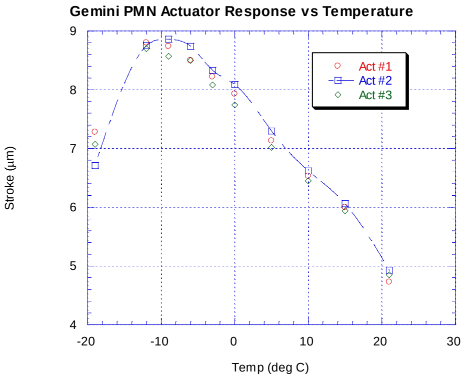


Figure 6. Measured Displacement vs. Temperature for typical deformable mirror actuator

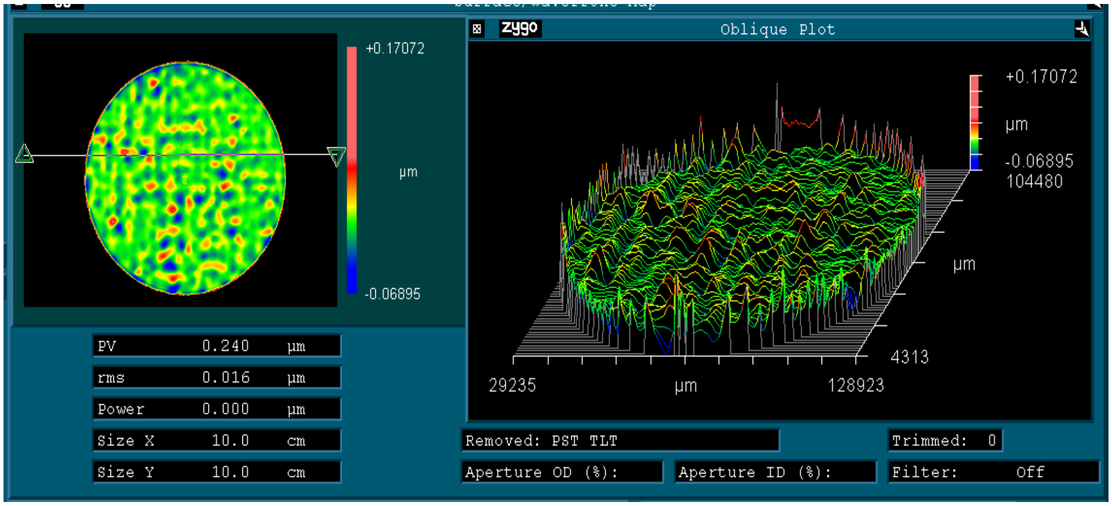
2.2 Performance of a 5mm Spaced Deformable Mirror

AOX designs its deformable mirrors to have specific characteristics so that the response is identical no matter the actuator spacing. It's important to maintain stress and stiffness to produce the same influence function no matter how large or small the mirror. The actuators used in 5 mm mirrors (Figure 7) have the same stroke characteristics as the 7 mm spaced mirrors. By carefully designing the facesheet, response can be made identical with regard to influence function, residual error, and polishing.

Figure 7. 941-channel deformable mirror with 5 mm spacing

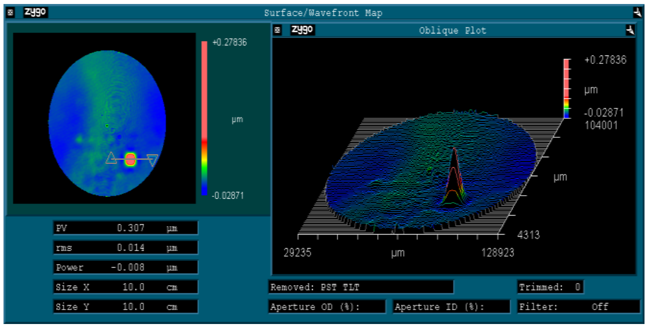
Measurements made of a typical 5mm spaced mirror show characteristics identical to those of the older 7 mm spaced design. The mirror's design calls for a 10% influence function with average actuator stroke of 4 microns. Figure 8 shows the mirror surface after applying a set of commands to flatten the mirror. Over the full aperture it shows a residual error of 13 nm rms which is typical of a AOX deformable mirror. Influence function measurements show the same similarities. Figure 9 shows the 2D influence function measurement made when pushing a single actuator.

Figure 10 shows a 1D cut through the center. A 10% value of the central displacement appears at the next nearest neighbor as predicted by the design. The characteristics undershoot beyond that is a distinguishing feature of a deformable mirror and duplicates exactly the shape seen on the lower density mirrors.



PV 0.240 µm
rms 0.016 µm
Power 0.000 µm
Size X 10.0 cm
Size Y 10.0 cm
Removed: PST TLT
Trimmed: 0
Aperture OD (%):
Aperture ID (%):
Filter: Off

Figure 8. Measured response of 349ch deformable mirror after flattening commands. The residual figure error of 16 nm rms is typical for these types of mirrors.



PV 0.307 µm
rms 0.014 µm
Power -0.008 µm
Size X 10.0 cm
Size Y 10.0 cm
Removed: PST TLT
Trimmed: 0
Aperture OD (%):
Aperture ID (%):
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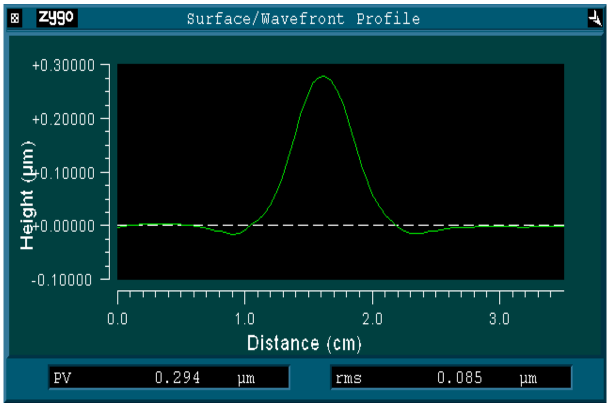
Figure 9. Influence function measurement of 349ch 5mm spaced mirror. The measurement displays the same features as that of larger spacing deformable mirrors.



PV 0.294 µm

rms 0.085 µm

Figure 10. Detailed view of the influence function measurement. This shows all the classic features of a standard influence function. The value at the nearest neighbor is 10% of the peak displacement and shows the undershoot between the 1st and 2nd neighbor due to the facesheet stiffness.

3. PHOTONEX DEFORMABLE MIRROR

The problem a mirror designer faces when trying to increase the actuator packing density is where to put the wires. AOX has found that there is roughly a 5 mm spacing limitation beyond which discrete actuators no longer provide an adequate solution. As had been seen earlier in this paper, the PMN actuators are built similarly to ceramic capacitors. Electrode material is interleaved between PMN ceramic to form a parallel plate capacitor. AOX took this configuration and turned it 90 degrees making the electronics run perpendicular to the facesheet rather than parallel. In this way ceramic modules can have all the wiring emerge at the back of a module allowing tighter spacing.

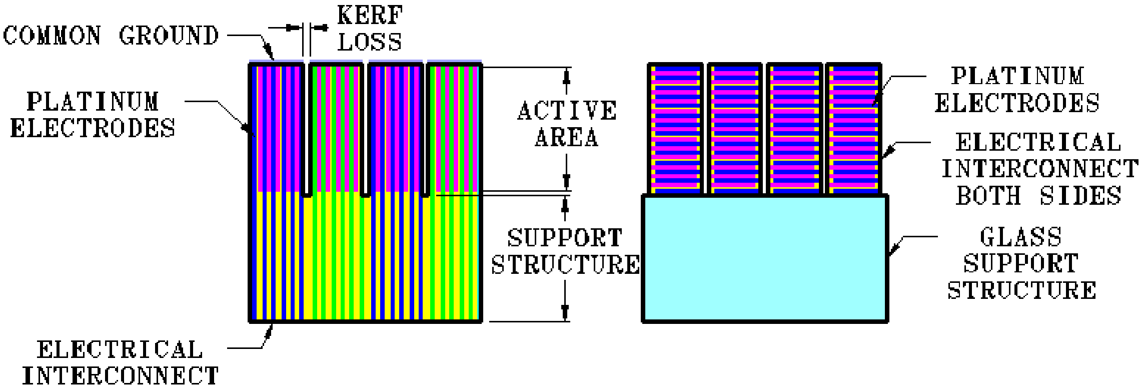


Figure 11. Comparison of modular mirror approach and conventional discrete actuator approach. The modular approach on the left has the electrodes running perpendicular to the facesheet. The electrical interconnect then appear at the back freeing up substantial space within the mirror structure.

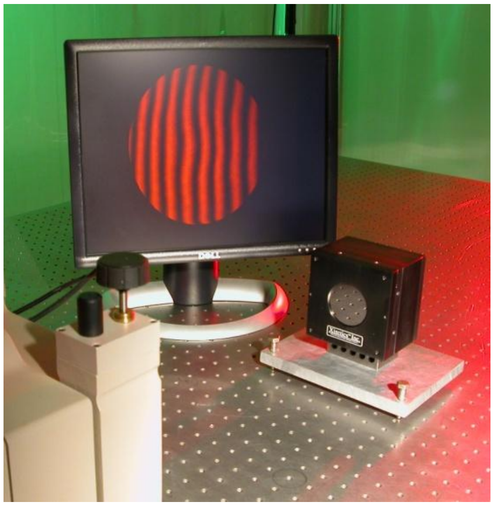
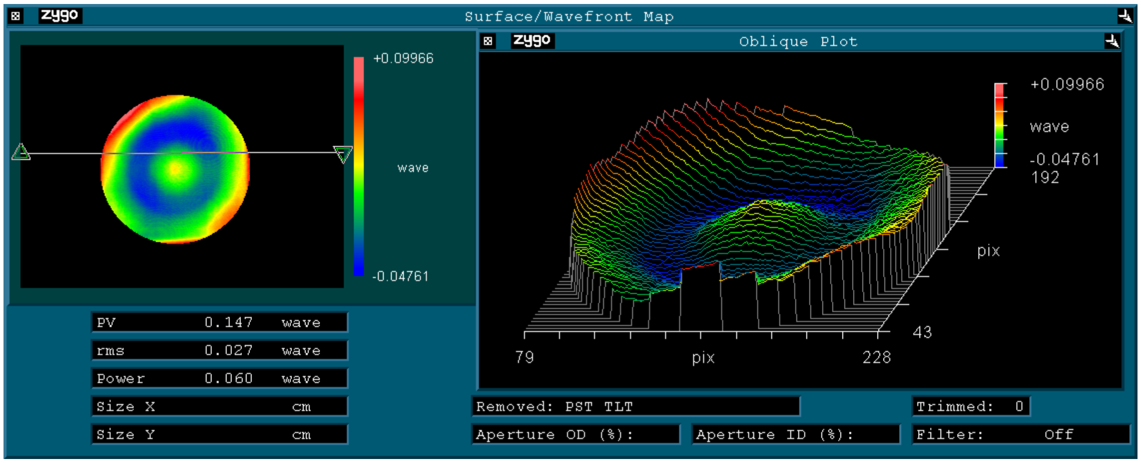


Figure 12. Example of a 349-channel Photonex deformable mirror. The aperture of only 53 mm is substantially smaller than a conventional deformable mirror which has a 160 mm aperture

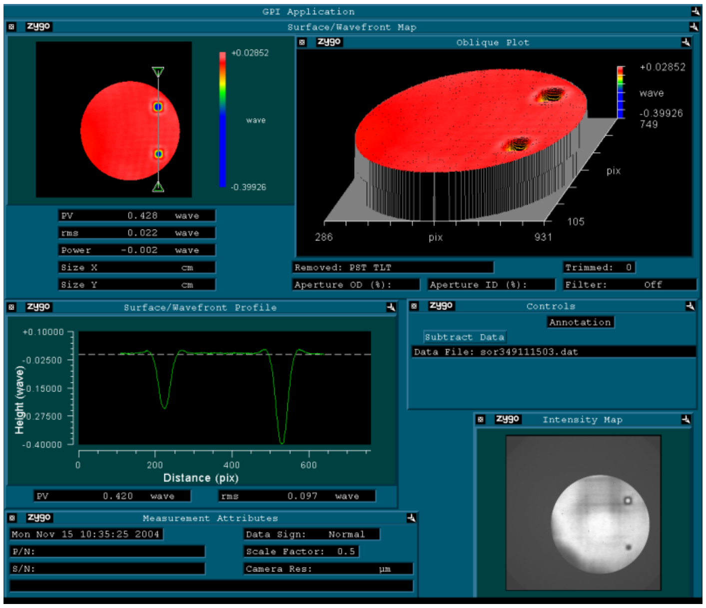
As with the discrete actuator mirrors, the mirrors are designed to have as identical performance characteristics as possible for all mirror sizes. In this way users know what to expect from AOX mirrors and can easily predict their system's performance.

Figure 13 and Figure 14, we see measurements made on a 349-ch modular mirror that has 2.5mm actuator spacing. This mirror uses a sealed facesheet and produces polished figure comparable to AOX discrete actuator mirrors. The influence function measurements show the 10% values routinely designed into AOX mirrors.



PV 0.147 wave
rms 0.027 wave
Power 0.060 wave
Size X cm
Size Y cm
Removed: PST TLT
Trimmed: 0
Aperture OD (%):
Aperture ID (%):
Filter: Off

Figure 13. Surface Measurements of 349-ch 2.5mm Modular Mirror in the unpowered state.



PV 0.428 wave
rms 0.022 wave
Power -0.002 wave
Size X cm
Size Y cm

Removed: PST TLT
Trimmed: 0
Aperture OD (%):
Aperture ID (%):
Filter: Off

Data File: sor349111503.dat

PV 0.420 wave
rms 0.097 wave

Mon Nov 15 10:35:25 2004
P/N:
S/N:
Data Sign: Normal
Scale Factor: 0.5
Camera Res: µm

Figure 14. Influence function measurement of a 349-ch modular mirror. The Photonex mirrors are designed to produce response characteristics as close as possible to the original conventional mirrors.

4. INTEGRATED WAVEFRONT CORRECTOR

Adaptive optics systems increasing complexity have shown the need to simplify the setups and begin merging functionality into individual components. AOX development of the Integrated Wavefront Corrector (IWC) intends to combine the capabilities of a fast-steering mirror and deformable mirror into one package. This is advantageous for the following reasons. Generally, adaptive optics requires relaying the pupil plane of the system to all the components that will be modifying the phase of the collected wavefront. This insures that the correction occurs to a wavefront that is purely phase and not a combination of phase and intensity. To relay the phase front requires reimaging optics for each of the active components in the system. If the designer can combine functions into a single optic, significant space savings result. Additionally, fewer optics means better throughput and less distortion.

Figure 15. AOX design of a 177-channel deformable mirror with an integrated wavefront corrector. The IWC is capable of 0.5 mrad of tilt at 100 Hz.

Figure 15 shows a picture of an example of a deformable mirror and an integrated wavefront corrector. The basic mirror uses an AOX 177-channel mirror modified to mount within the tilt stage. The mirror has a 98 mm aperture requiring tilt actuators with a large amount of displacement (> 60 microns). The deformable mirror has characteristics shown in

Table 1. These are typical deformable mirror characteristics; again AOX always desires to insure mirrors meet the same performance characteristics unless otherwise specified.

Number of Actuators	177
Mechanical Stroke	4 µm
Actuator Capacitance @ 1kHz	2 µF
Operating Voltage	100 V (70V ± 30V)
Maximum Interactuator Stroke	2 µm
Influence Function	10% at nearest neighbor
Hysteresis	< 1%
Actuator Frequency Response	> 4 kHz
Mirror Surface Figure	λ/10 rms
Clear Aperture	98.2 mm
Coating	Customer Supplied

Table 1 - Performance characteristics of the 177 channel deformable mirror

Tilt stages are found in Table 2. Take note of the relatively high frequency response of the tilt system. Despite the large size of the deformable mirror and the associated mass, the high force capability of the AOX actuators provides the ability to drive to higher frequencies.

Actuators	6 actuators per stack
Mechanical Stroke	> 60µm
Actuator Capacitance	< 250 microfarads
Operating Voltage	80v (50v±30v)
Actuator Frequency Response	840 Hz
System Tilt Across Aperture	0.5 mrads

Table 2 - Tilt Stage Characteristics

5. SURFACE PARALLEL ARRAY DM

The Surface Parallel Array (SPA) DM is fabricated by bonding a micro-machined electrostrictive ceramic actuator array to a thin, optically polished facesheet. Electrical connections are made via a flexcircuit. This structure is shown in Figure 16. The bonding of the actuator array is performed after the facesheet is coated allowing the application of stress balanced coating designs.

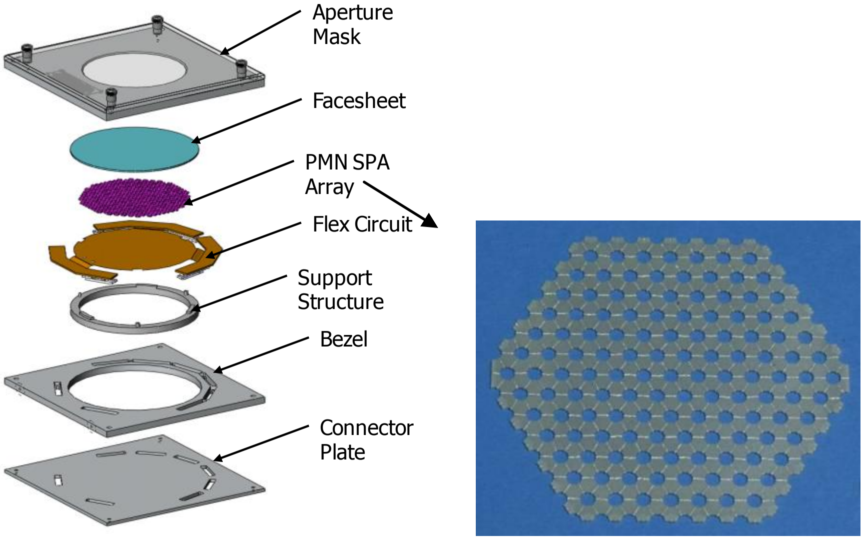


Figure 16. Exploded view of SPA DM

6. DISCRETE ACTUATOR SURFACE PARALLEL ACTUATED DM

Conventional deformable mirrors use actuators normal to the optical surface. The overall stroke of the deformable mirror is limited by the maximum stroke of a single actuator. For high energy applications, large stroke is needed to mitigate the laser induced thermal errors while high spatial and temporal correction is still required for the atmospheric errors. While the actuator length can be increased to produce larger stroke, the capacitance increases thereby reducing the bandwidth and compromising the higher order response. By utilizing the SPA configuration as seen in Figure 17 large stroke and high spatial correction are enabled while keeping high bandwidth. Actuators are embedded directly into the silicon carbide isogrid structure which serves as both the mirror face and the reaction structure. Activating a single actuator in this configuration induces a local bending moment while activating an array enables additive stroke and large global deformation across the optical surface. Small, low capacitance actuators produce large deflections while keeping peak current requirements low thereby enabling high bandwidth operation. Fine control actuators located within the isogrid compensate for thermal print-through and higher order errors induced by laser irradiance mapping.

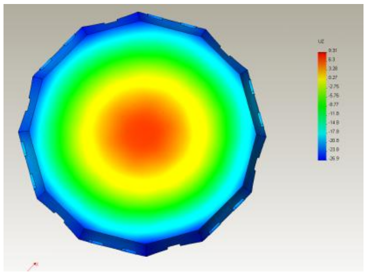


Figure 17. SPA DM Produced 40 um of Deformation

An analysis of the overall stroke produced by a SPA DM with actuators capable of producing 4 microns of displacement can be seen in Figure 17. This shows that the SPA DM can correct low spatial frequency aberrations of amplitudes up to 40 microns. To correct for the higher spatial frequency aberrations, fine control actuators will be placed within a cathedral rib structure that is closer to the optical surface. The locations of the global control and fine control actuators can be seen in Figure 18. By placing the actuator inside the stiffening rib structure, a localized influence function is produced. The shape of the fine control actuator influence function (Figure 19) is very similar to that of a classical deformable mirror that has been typically used for the correction of atmospheric distortions and can correct for local deformations in optical elements due to hot spots in the laser, or thermal quilting of the lightweight optics.

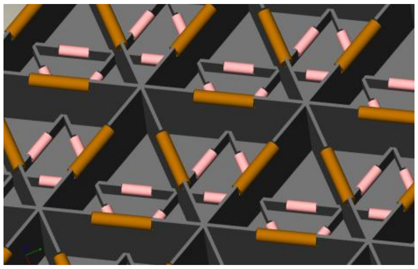


Figure 18. Fine and Global Control actuators integrated into SiC isogrids

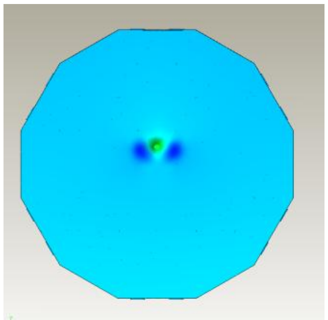


Figure 19. Fine Control Influence function

The silicon carbide mirror substrate is manufactured with the CERAFORM casting process which has recently achieved a TRL level of 8/9. Ultra-lightweight structures can be rapidly fabricated with stiffening ribs as thin as 0.030 inches and rib heights as tall as 4 inches. With the high elastic modulus, the low mass density, and the ability to fabricate structures utilizing high thickness to height aspect ratios, surface parallel deformable mirrors can be designed to produce 40 microns of deformation with a first resonant frequency well above 2500 Hz. The first resonant frequency of this structure is a plate bending mode which can be seen in Figure 20. Since the actuators add to the plate stiffness of the system, an impedance matched design between the actuators and silicon carbide structure will produce an optimally stiff system. Silicon carbide has very high thermal conductivity and low thermal expansion that matches that of the PMN actuators. The high thermal conductivity of silicon carbide will minimize temperature gradients through the thickness of the mirror which will minimize the thermal distortion and has the capability to rapidly dissipate localized hot spots which will minimize the probability of thermally induced coating failures. The silicon carbide rib structure is a perfect shape and size to maximize convection heat loss through a semi infinite fin. The SPA greater surface area enables an order of magnitude better heat rejection than conventional DMs.

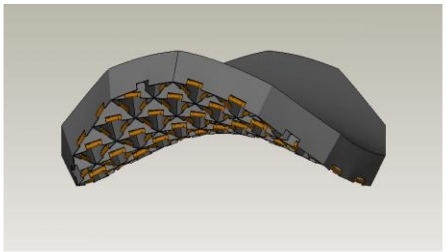


Figure 20. Impedance matched design maximizes system resonant frequency

7. SUMMARY

AOX has developed new mirror technologies that strive to produce more responsive optical systems. The discrete actuator mirrors have pushed actuator spacing down to 5 mm while maintaining the performance characteristics of the older and larger mirrors. With the need of more compact systems, Photonex modules give the designer the option of using much smaller deformable mirrors with actuator spacing as small as 1 mm. This means that either the system can be made much smaller or that more channels can be placed within the same space. The nature of the spacing also means the optical designer can tailor the mirror size to the beam size, eliminating the need for expensive beam expanders and compactors the rob performance and introduce distortion. The Integrated Wavefront Corrector provides further tools to make more compact optical systems by integrating tilt and high order correction into one package. Compact systems do not necessarily mean that design gives up displacement. The SPA DM shows a way to generate larger displacements in a smaller package while keep stress lower and providing a high speed correction.