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Pocket Deformable Mirror for Adaptive Optics Applications

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“POCKET” DEFORMABLE MIRROR
FOR ADAPTIVE OPTICS APPLICATIONS

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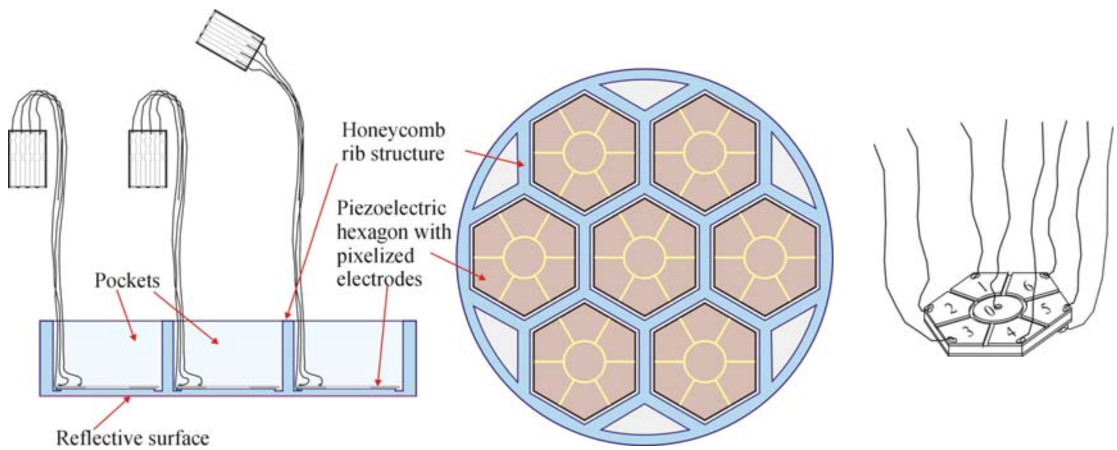
INTRODUCTION

Adaptive/active optical elements are designed to improve optical system performance in the presence of phase aberrations. For atmospheric optics and astronomical applications, an ideal deformable mirror should have sufficient frequency bandwidth for compensation of fast changing wave front aberrations induced by either atmospheric turbulences or by turbulent air flows surrounding a flying object (air optical effects). In many applications, such as atmospheric target tracking, remote sensing from flying aircraft, boundary layer imaging, laser communication and laser beam projection over near horizontal propagation paths the phase aberration frequency bandwidth can exceed several kHz. These fast changing aberrations are currently compensated using relatively small size (a few inches or less) deformable mirrors, such as micro-electro-mechanical systems (MEMS) based DMs [1], piezoelectric deformable mirrors based on semi-active or passive bimorph elements (bimorph mirrors) [2,3], or DMs with an array of push-pull type actuators [4-8]. These DMs are difficult to scale to larger size without either significant reduction of their operational speed or substantial increase of optical system complexity and cost, when DM scaling is performed by combining small size DMs to a larger size phased array. To match small size DM diameter d the optical telescope aperture of diameter $D>>d$ is re-imaging with demagnification factor $M = D/d$. In most practical applications the demagnification factor M can be extremely large (on the order of 100 or even more). Re-imaging of the telescope pupil with a high magnification factor requires installation of additional optical elements, including one or more optical relay systems, resulting in a substantial increase of size, weight, and cost of the entire optical system. This high magnification factor also makes it highly sensitive to vibrations, “high g” and high-thermal gradient environmental factors.
The deformable mirror described in the presented paper intends to overcome the mentioned drawbacks of the existing DMs by offering the deformable mirror design scalable up to the aperture diameter of the optical telescope primary mirror. The proposed Pocket-DM (PDM) can be directly used as a primary adaptive mirror of optical telescope

and laser beam delivery system eliminating the need for additional optical elements used for incorporation of a small size DM into telescope optical train.

POCKET MIRROR DESIGN AND MANUFACTIRING

The proposed deformable mirror contains an array of pockets machined on backside of a bulk substrate of glass or composite material, Fig.1A. A dielectric or metal layer reflecting light is deposited on the front surface of the substrate. The thickness of the substrate inside the pocket area is significantly less than outside the pocket. A thin layer of an electro-active material, e.g. piezo-electric ceramics, is bonded to the bottom surface of each pocket.



A

B

Fig. 1. A-The design of the 7-pocket deformable mirror. Each pocket contains 7 pixel piezoelectric ceramic hexagon (B), bonded to the bottom of the pocket. The electrodes on outer side of hexagon are shown by numbers from (0) to (6).

The patterned conductive films (pixels) are deposited on both sides of the layer of electro-active material, Fig.1B. External voltage applied to the selected areas of the piezoelectric layer through the electrical wires connected to the pixels induces the contraction or extension of the layer. The transversal electro-mechanical effect based on d_{31} module of piezoelectric material is used for the layer deformations. Due to semi-passive nature of the bimorph structure formed by the piezoelectric layer and bottom layer of the pocket the reflective surface possess the convex or concave deformation in response to contraction or to expansion of actuator.

The fabricated sample of the pocket deformable mirror is shown in Fig.2.
The performance of the mirror was evaluated using the Zygo interferometer.
Each pixel from (1) to (6) in Fig.1B of every pocket is connected to two external high-voltage a. c. power supply, while the central pixel (0) is connected to the third high-voltage power supply.

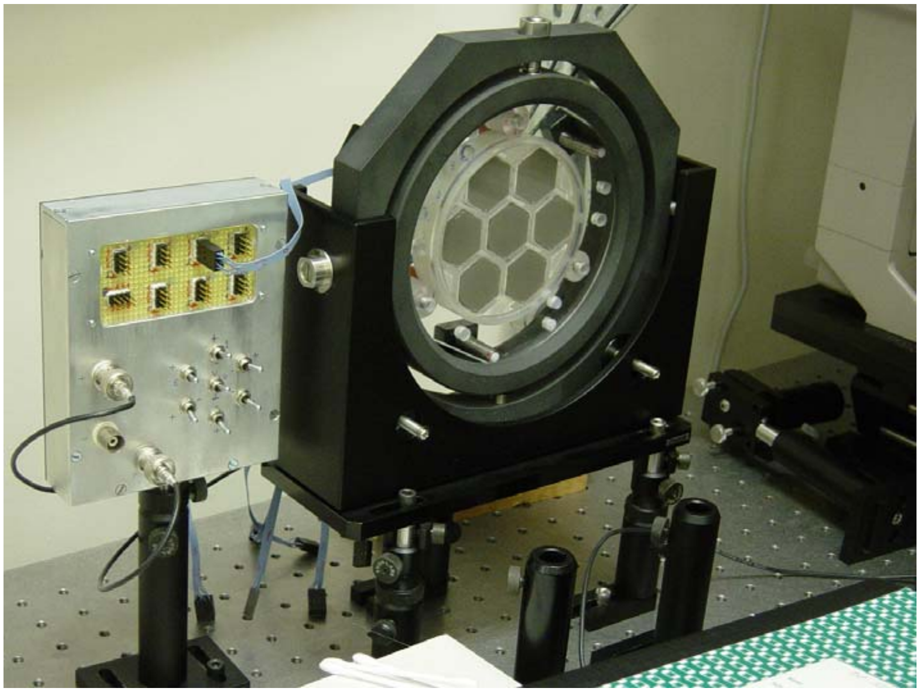


Fig.2. 7-pocket 49-channel deformable mirror with a. c. voltage station (left).

Selecting the pixels of the piezoelectric layer results in deformation of the pocket mirror. In Fig.3 these deformations (response functions) are shown for selected pixels of one pocket as well as for a combination of pixels.

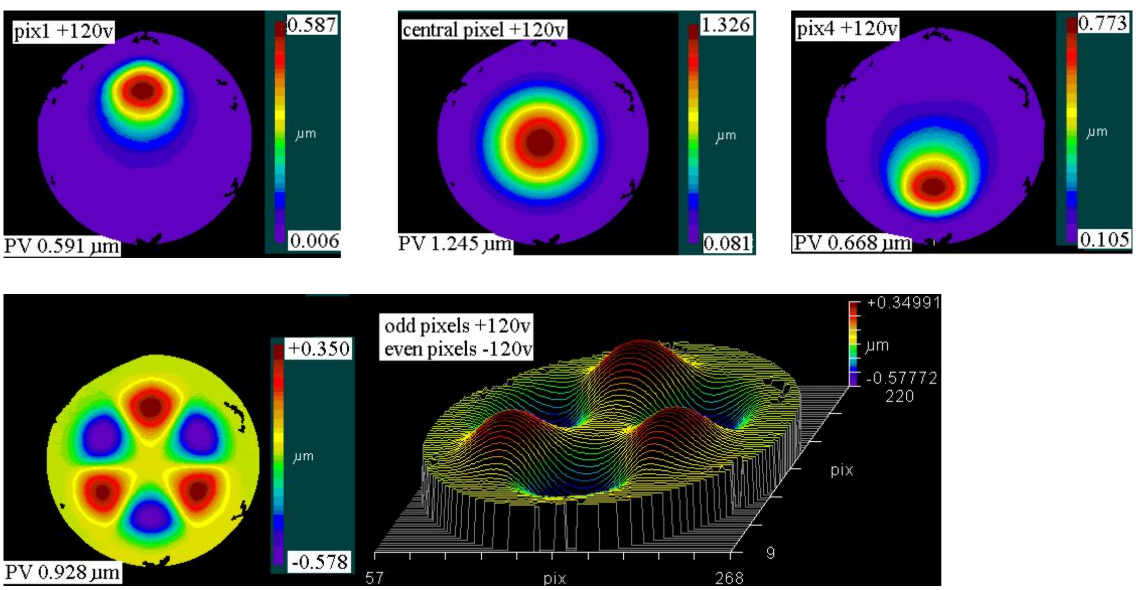


Fig.3. Response functions of one pocket when the external voltage is applied to the selected pixels.

This demonstrates that the surface can be individually manipulated, with each channel influencing an area of approximately 1 cm diameter. This property of the manufactured mirror can be useful for the correction of high spatial frequency atmospheric turbulences.

In Table 1 the mirror surface deformation peak values are presented for the corresponding combinations of voltages applied to the selected electrodes.

Table 1. Peak values of the reflective surface deformations induced with some combinations of the selected pixels under control voltages.

No	Voltages applied to a single pocket electrodes	Deformation peak value, µm
1	All electrodes at +30V	0.5
2	All electrodes at +60V	1.2
3	All electrodes at +100V	2.2
4	All electrodes at –100V	-2.2
5	Electrode (1) at +120V	0.58
6	Electrode (4) at +120V	0.66
7	Electrode (0) at +120V	1.2
8	Electrodes (1), (3), (5) at +120V, electrodes (2), (4), (6) at –120V	0.9
9	Electrodes (1), (2), (3) at -90V, electrodes (4), (5), (6) at +90V	1.5
10	Electrodes (3), (6) at +100V, electrode (0) at –100V	1.2
11	Electrodes (2), (4), (6) at +100V, electrode (0) at -100V	1.1

In the case of multi-pocket PDM the areas of mirror between walls of neighbor pockets form the rib structure, providing high stiffness to the PDM's overall optical surface when the thickness of glass and thickness of ribs between the neighboring pockets are properly chosen. The ribbing pocket structure of the pocket mirror allows one to manufacture the mirror surface with good optical quality.

Fabrication of the multi-pixel thin-layer electro-active actuators as well as bonding them inside the pockets are significantly simpler and less expensive than fabrication of mirrors with push/pull actuators located outside of the supporting back structure with a comparable density of actuators per unit area of mirror.

A unique property of the PDM is that it can provide scalable DM architecture with local (inside pocket) compensation of low order phase aberrations. Independent of the number of pockets or mirror diameter, the PDM operational frequency bandwidth depends solely on the dynamic characteristics of a single pocket. This allows the manufacturing of large aperture size DMs with operational bandwidths on the order of tens of kHz.

In Fig's. 4 and 5 the examples of the surface deformation are shown for some combinations of voltages, applied to the pocket electrodes (the same voltages for each pocket).

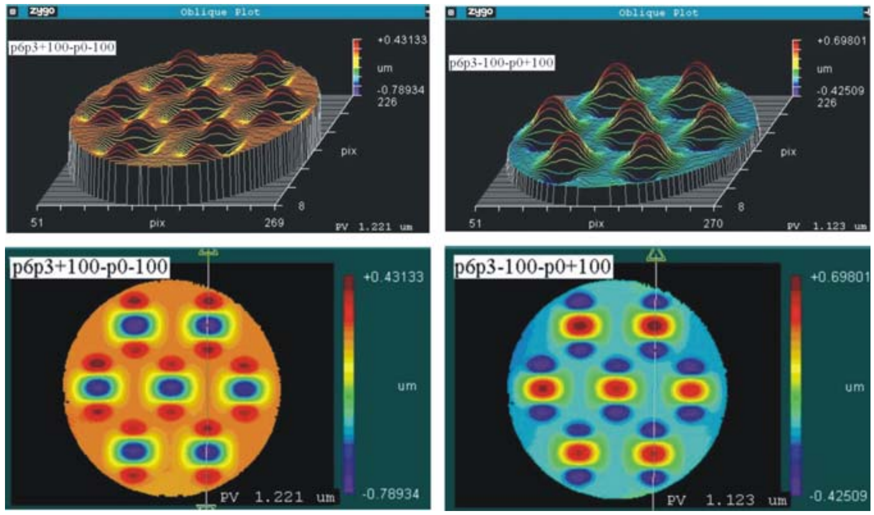


Fig.4. Left - Surface profile of 7-pocket DM if pixels (6) and (3) are at +100V, pixel (0) is at –100V. Right – opposite polarities are applied to the same pixels in each pocket.

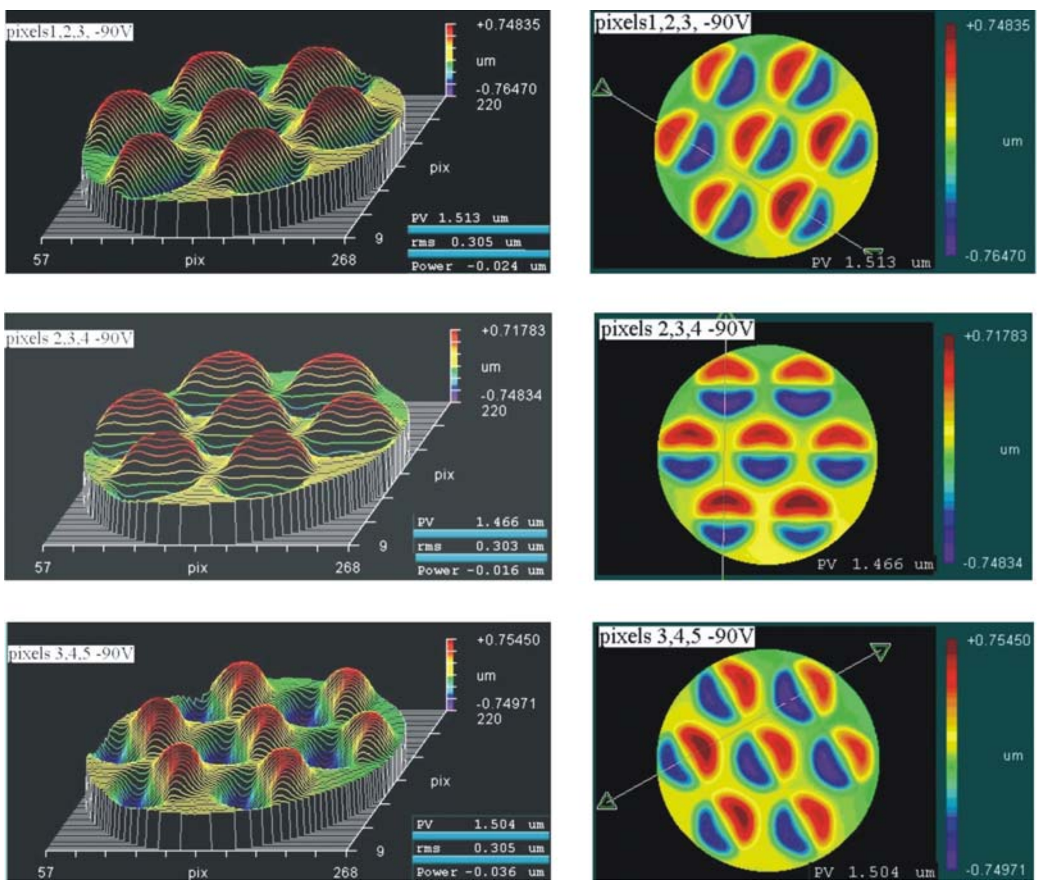


Fig.5. Surface profile of the 7-pocket mirror if three neighbor pixels are at +90V, and other three are at –90V. “Scanning” the azimuth direction.

The first resonance of each pocket was measured while a sine wave voltage was applied to all pixels, or to central pixels (0), or to a single side pixel from (1) to (6). The resonance frequency was determined as a frequency when the amplitude of deviation of the reflected laser beam showed a sharp increase. The scheme of setup is show in Fig.6. The resonance frequency for the manufactured mirror was found equal to 15 kHz.

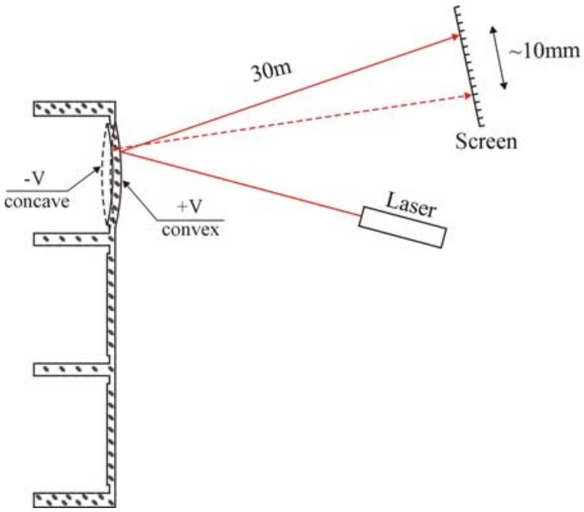


Fig.6. Setup for measurement of the resonance frequencies of the deformable areas of pockets.

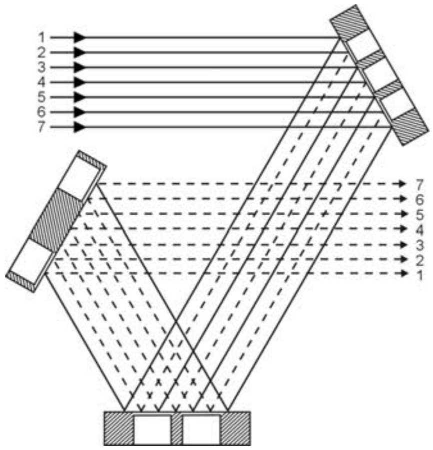
The obtained value of the first resonance describes the focus-defocus mode of the pocket bottom as it is shown in Fig 6. This mode was excited not only when all pixels of the pocket are driven in phase, but as well when any separate pixel of the pocket is driven. The resonance frequency was always approximately the same.

POCKET MIRRORS IN ADAPTIVE OPTIC SYSTEMS

According to the presented approach a large deformable mirror can be fabricated by means of scaling the number of the described pockets. The shape of pockets can arbitrarily chosen e.g. be triangular, rectangular, hexagonal etc. The PDM can contain pockets of different shapes. The number of control channels at each pocket depends on the chosen number of conductive areas deposited on the actuator plate.

Due to good mechanical decoupling between pockets the influence functions of separate channels (pixels) are strongly restricted with the dimension of one pocket, hence the high order spatial frequencies of the atmospheric induced aberrations can be controlled with high speed in range exceeding 10kHz.

The PDMs with different geometry of pockets can be combined in a single optical system aiming to increase wavefront phase aberration compensation capabilities and eliminate uncontrollable PDM zones related with ribbing spacing between the mirror pockets. The Fig. 7 shows the combination of three pocket mirrors having the overlapping control areas. All beams 1-9 of the incoming wave front have a controllable phase after they are reflected sequentially from these 3 mirrors.



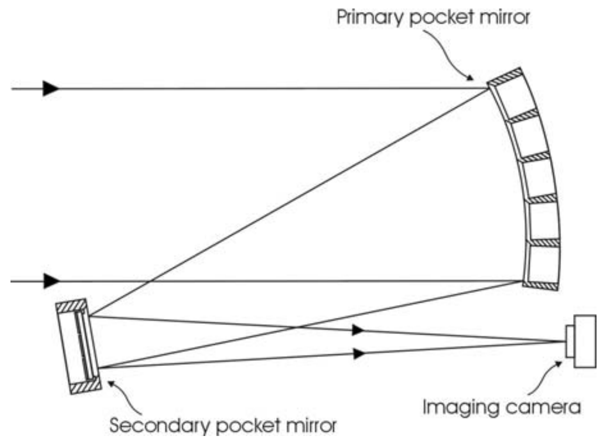


Fig.7. The part of adaptive optic system composed from pocket mirrors with over lapping control areas.

Fig.8. Telescope utilizing pocket mirrors.

In Fig.8 the telescope is shown, containing the multi-pocket primary mirror and the deformable secondary mirror with a single pocket. The primary mirror controls the high order aberrations whereas the secondary mirror controls the low-order aberrations.

SUMMARY

The deformable mirror with adaptive optics elements located inside of mirror is discussed. The 49 channel, 100mm diameter deformable mirror is fabricated with bimorph piezoelectric actuators inside of mirror pockets.

The frequency bandwidth exceeding 10kHz is shown.

The amplitude of the response for focus-defocus mode with a stroke of more than 4μms was obtained. For the highest spatial frequency a stroke of about 1.5μm was obtained.

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REFERENCES

1. T. Weyrauch, M. A. Vorontsov, L. A. Beresnev, and Ling Liu, “Atmospheric compensation over a 2.3 km propagation path with a multi-conjugate (piston-MEMS/modal DM) adaptive system”, Proc. SPIE, vol.5552, pp.73-84 (2004).
2. S. A. Kokorowski, J. Opt. Soc.Am. 69, 181 (1979).

3. M. A. Vorontsov, A. V. Kudryashov, S. I. Nazarkin, and V. I. Shmalhausen, “Flexible mirror for adaptive light-beam formation system”, Sov. J. Quantum Electron. 14(6), pp.839-841 (1984).
4. J. W. Hardy, “Active Optics: A New Technology for the Control of Light”, Proc. IEEE, vol. 66, No. 6, pp. 651-697, Jun. 1978.
5. M. A. Ealey “Actuators: Design Fundamentals, Key Performance Specification, and Parametric Trades”, SPIE vol. 1543, Active and Adaptive Optical Components, 1991, pp.346-362.
6. M. A. Ealey and J. A. Wellman, “Deformable Mirrors: Design Fundamentals, Key Performance Specifications and Parametric Trades”, SPIE vol. 1543, Active and Adaptive Optical Components, 1991, pp. 36-51.
7. A. Phillips, M. Sogard, “Deformable mirror actuation system”, US Patent 6,989,922, Jan. 24, 2006.
8. H. E. Bennett, J. J. Shaffer, J. D. Westfall, R. C. Romeo, M. C. Creusere, “Adaptive optics mirror”, US Patent 6,902,281, Jun. 7, 2005.
9. hν-photonics, Wailuku, Hawaii.
10. Piezo Systems Inc., Cambridge, Massachusetts.
11. D. L. Fried, “Statistics of a geometric representation of wavefront distortion”, J. Opt. Soc. Am. 55, pp.1426-1433 (1965).