High-power visible-laser effect on a Boston Micromachines' MEMS deformable mirror

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ABSTRACT

Continuous-facesheet and segmented Boston Micromachines Corporations' (BMC) Micro-Electrical Mechanical Systems (MEMS) Deformable Mirrors (DM) have been tested for their response to high-power visible-wavelength laser light. The deformable mirrors, coated with either protected silver or bare aluminum, were subjected to a maximum of 2 Watt laser-light at a wavelength of 532 nanometers. The laser light was incident for time periods from minutes to 7 continuous hours. Spot heating from the laser-light is measured to induce a local bulge in the surface of each DM. For the aluminum-coated continuous facesheet DM, the induced spot heating changes the surface figure by 16 nm rms. The silver-coated continuous-facesheet and segmented (spatial light modulator) DMs experience a 6 and 8 nm surface rms change in surface quality with the laser at 2 Watts. For spatial frequencies greater than the actuator spacing (300 µm, the laser induced surface bulge is shown to be removable, as the DMs continued to be fully functional during and after their exposure. Over the full 10 mm aperture one could expect the same results with a 15 Watt laser guide star (LGS). These results are very promising for use of the MEMS DM to pre-correct the outgoing laser light in the Laboratory for Adaptive Optics' (LAO) laser uplink application.

1. INTRODUCTION

The Laboratory for Adaptive Optics (LAO) at the University of California, Santa Cruz, in partnership with the Lick Observatory, has pioneered innovative techniques for improving the resolution of telescopes by using adaptive optic systems that remove aberrations caused by atmospheric turbulence.

Among these systems is the first Micro-Electrical Mechanical Systems (MEMS) deformable mirror-based AO system — Villages. In its 3 years of existence, the Villages (Visible Light Laser Guidestar Experiment) AO system, attached to the back of the 40" Nickel telescope at Mount Hamilton, has achieved diffraction limited images for V (550 nm) through I bands (880 nm) for both closed and open-loop operations using a Boston Micromachines (BMC) 144-actuator MEMS deformable mirror as the wavefront corrector[1,2].

In continuing to serve as an on-sky testbed for novel AO ideas, the Villages experiment is considering the use of a second Boston Micromachine Corporation's MEMS DM for laser uplink correction. In laser uplink AO, a deformable mirror pre-corrects the outgoing laser for atmospheric turbulence. Villages will use a 10 Watt
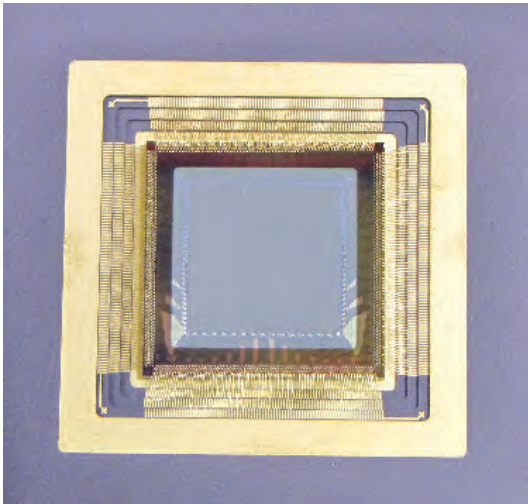
Figure 1. Image of the 1024-actuator continuous-facesheet silver-coated DM. The active DM area is inner most reflective region, (1 cm^2) surrounded by the gold wires that connect to the individual actuators.

laser that will launch out of the AO system, off of the DM, then the secondary and primary mirrors of the Nickel telescope, to form a diffraction limited spot in the sodium layer at an altitude of 90 km.

Forming a smaller laser spot in the mesosphere, offers several advantages. With the Villages optical setup, there is the potential to form a diffraction limited spot of 0.2 arcseconds, a factor of ten smaller then current uncorrected spot sizes[1]. Consequently, roughly a factor of 100 gain in signal-to-noise would be realized. Pairing this

with a wavefront sensor that can take advantage of this small spot, such as a pyramid wavefront sensor[3], allows for much more precise measurements of the atmospheric turbulence and AO in the visible wavelengths.

Certainly, this task of laser uplink AO places strict demands on the deformable mirror as not only must the DM be able to withstand the high optical power, it must be able to do this while operating at framerate of ~ kilohertz to keep up with the changing atmosphere. It must be able to do this night after night, sometimes with the laser-light being incident for several continuous hours, and still remain fully functional and without any permanent damage.

To this end, we have tested three Boston Micromachine Corp. MEMS deformable mirrors in tests designed to qualify their use in laser uplink AO.

2. THE MEMS DEFORMABLE MIRROR

Boston Micromachine Corporation's MEMS deformable mirrors are fabricated using a custom lithogrophy process[4]. The deformable mirrors' structure consists of alternating layers of polysilicon and oxide, with the latter being removed to
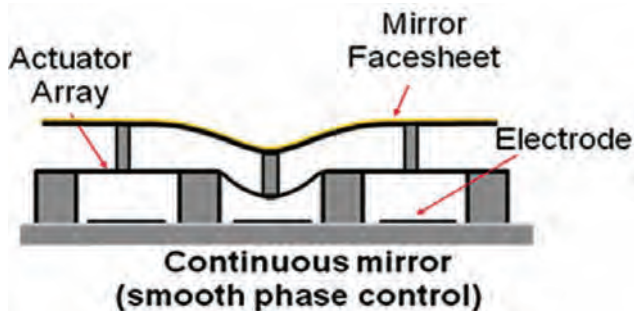

Figure 2. Schematic 3-D cross section showing 3 actuators of a continuous facesheet DM. Deflection in the surface is caused by an electostatic potential between the electrode and the poly-silicon layer above. The maximum stroke is 2 μm for these mirrors.
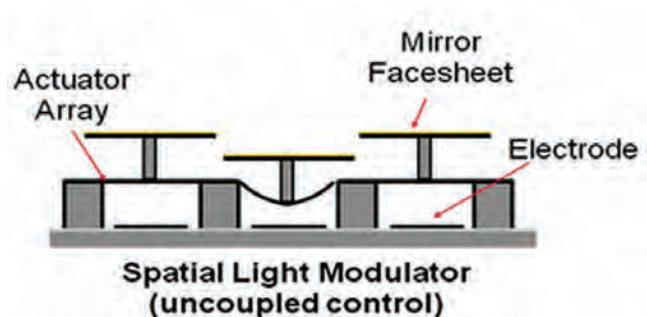

Figure 3. Schematic 3-D cross section showing 3 actuators of a spatial light modulator (SLM). The 2 μm spacing gives the DM a > 98% fill factor with no coupling between adjacent segments. The mirrors tested at the LAO moved in piston morion only.

allow the free standing structures to deflect under actuation. Deflection is achieved with capacitive electrostatic actuation. When an electrostatic potential is applied to the electrode, the double-cantilever plate above is deflected downwards. Consequently, this pulls down the attachment post which translates the deflection of surface of the mirror in a very highly controllable shape.

Three, 1024-actuator DMs have been tested: Two continuous-facesheet (3 µm thick silicon) DMs and one segmented (spatial light modulator, 8 µm thick silicon). The SLM and one of the continuous-facesheet DMs are coated with 100 nm of protected silver. The other continuous-facesheet DM is coated with roughly 70 nm of aluminum. Though these devices are often housed behind a window to guard against oxida-

tion, for the purposes of these tests the window was removed. The silver-coated DMs have an overlaying 10 nm layer of magnesium fluoride to guard against oxidation. The actuators for each mirror are arranged in a 32×32 grid with 300 µm pitch giving an active aperture of 9.6 mm—see Fig. 1.

3. TESTBED LAYOUT

Figure 4 represents the optical layout of the high-power laser test. The frequency-doubled neodymium-doped yttrium aluminum garnet (Nd:YAG) laser light (λ=532 nm) is incident on the MEMS DM after traveling 2.5 meters. The Gaussian-profile laser-light exits the Nd:YAG cavity, reflects off of two flat mirrors (M1 and M2) are used to increase the angle of incidence,
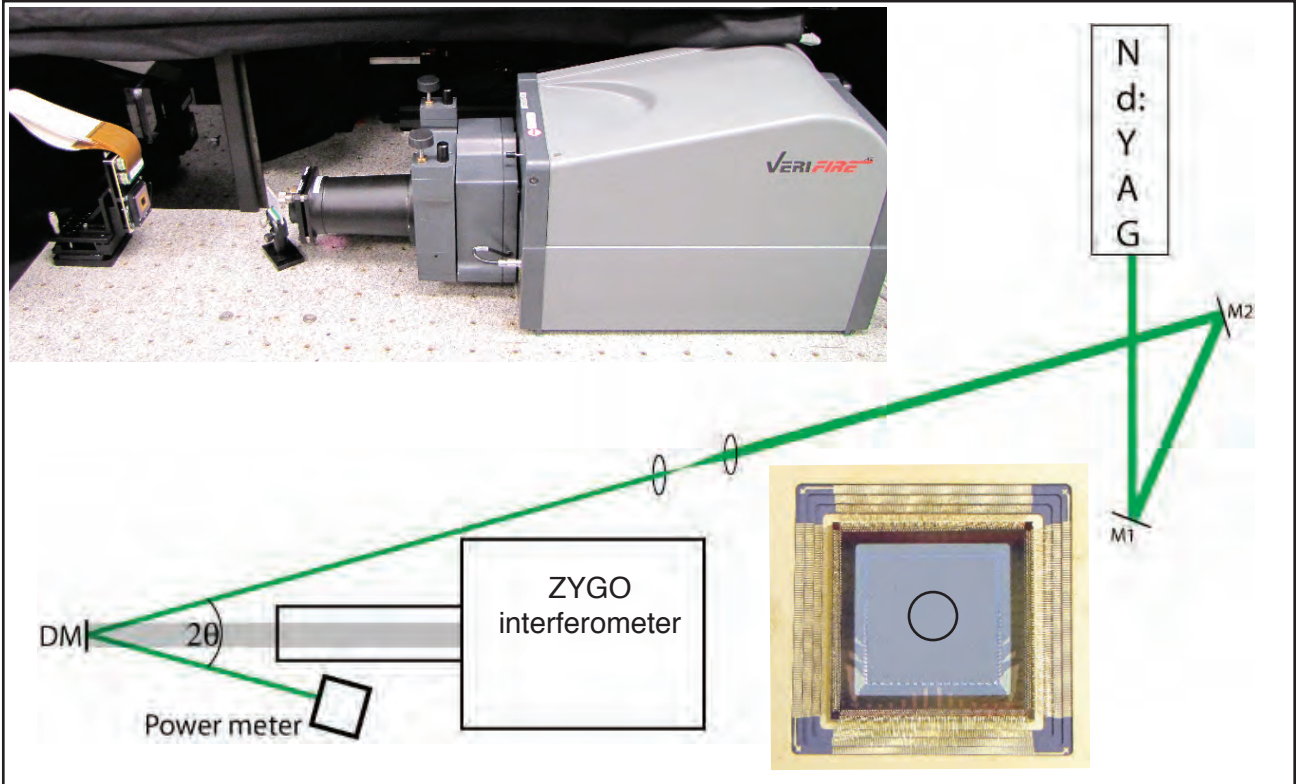

Figure 4. Schematic showing the testbed layout for the high-power test. Situated on the ExAO testbed at the LAO, the Gaussian-profile Nd:YAG laser light is incident on the DM after traveling 2.5 meters. Two flat mirrors (M1 and M2) are used to increase the angle of incidence to an angle θ of 12.3°. Measurements of the DM's surface are recorded with the Zygo interferometer. A 633 nm bandpass filter is placed in front of the Zygo to guard the CCD against any scattered laser light. Inset upper right: image of the DM (left) and Zygo interferometer (left) with the bandpass filter in place. Inset lower right: The silver-coated continuous-facesheet with circle representing the approximate location and size of the 3.5 mm beam on the DM.
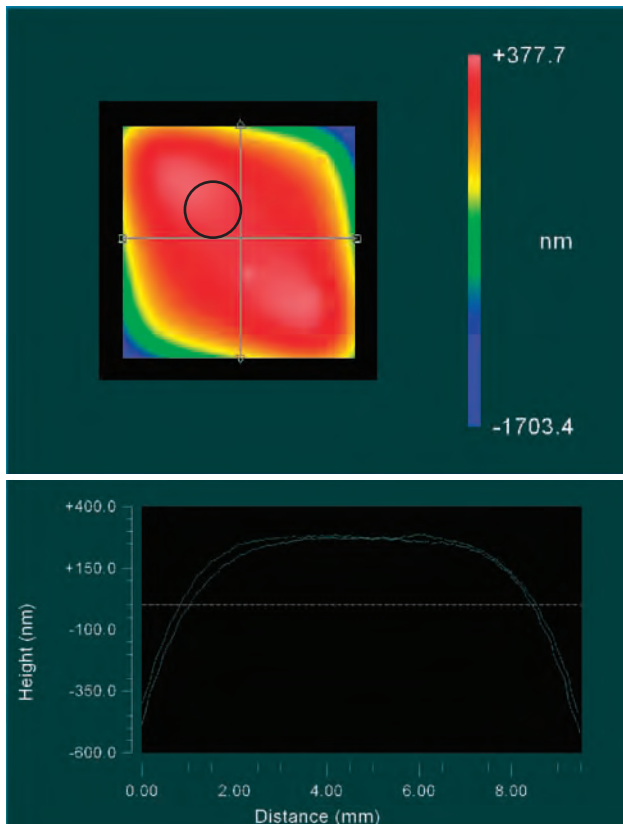
Figure 5. Zygo surface image (top) and corresponding lineouts of the 32×32 actuator continuous-faceheet aluminum-coated DM. The laser beam diameter and location of incidence are represented by the circle outline. For the response of the mirror to varying optical power refer to Fig. 6.

before traveling the rest of the 2.5 meters to the surface of the deformable mirror (DM). For some tests, a telescope pair of lenses is used at the half way point to reduce the incident beam from 3.5 mm to 1.75 mm to increase the incident power density. Measurements of the optical power are made with the Newport power meter (model 1917-C) placed after the DM. These measurements are then compared with measurements of the optical power recorded with the power meter in front of the DM. The Zygo VeriFire AT+ Fizeau interferometer is placed normal to DM's surface and records the surface response of the DM as the laser power is increased. The focal length (27 cm) and the body of the interferometer define the limiting incidence angle θ of 12.3°. A

633 nm bandpass filter (not shown in figure 4) is placed just in front of the Zygo lens at a 45°angle to protect the interferometer's CCD from any scattered laser light.

The beam profile was measured in-situ by placing the power meter on a micrometer stage, with 2 razor blades fastened a millimeter apart attached to the front of the power meter, and measuring the location of the beam that corresponds to the peak intensity. The beam diameter—within which 85% of the optical power is contained—is taken to the distance at which the peak intensity decreases by 0.135. A 1.75 mm beam diameter was measured with the telescope pair inserted.

4. TEST PROCEDURES AND RESULTS

The five steps of the test procedure for the three DMs are listed below:

1) Select either the 1.75 or 3.5 mm beam diameter.

2) Select location on the DM for the laser beam to be located. Areas were selected that were deemed far enough from the edges of the device but not to close to any uneven surfaces— see Fig. 5.

3) Ramp the laser power from 0 to 2 Watts in 0.1 Watt increments.

4) Record surface measurements after each increment in laser power.

5) Depending on what characteristic we wished to examine, the next step when at the maximum power of 2 Watts was either to:
 a) shutter the laser switch—laser power goes from 2 to 0 Watts without going step-wise back to 0 Watts.
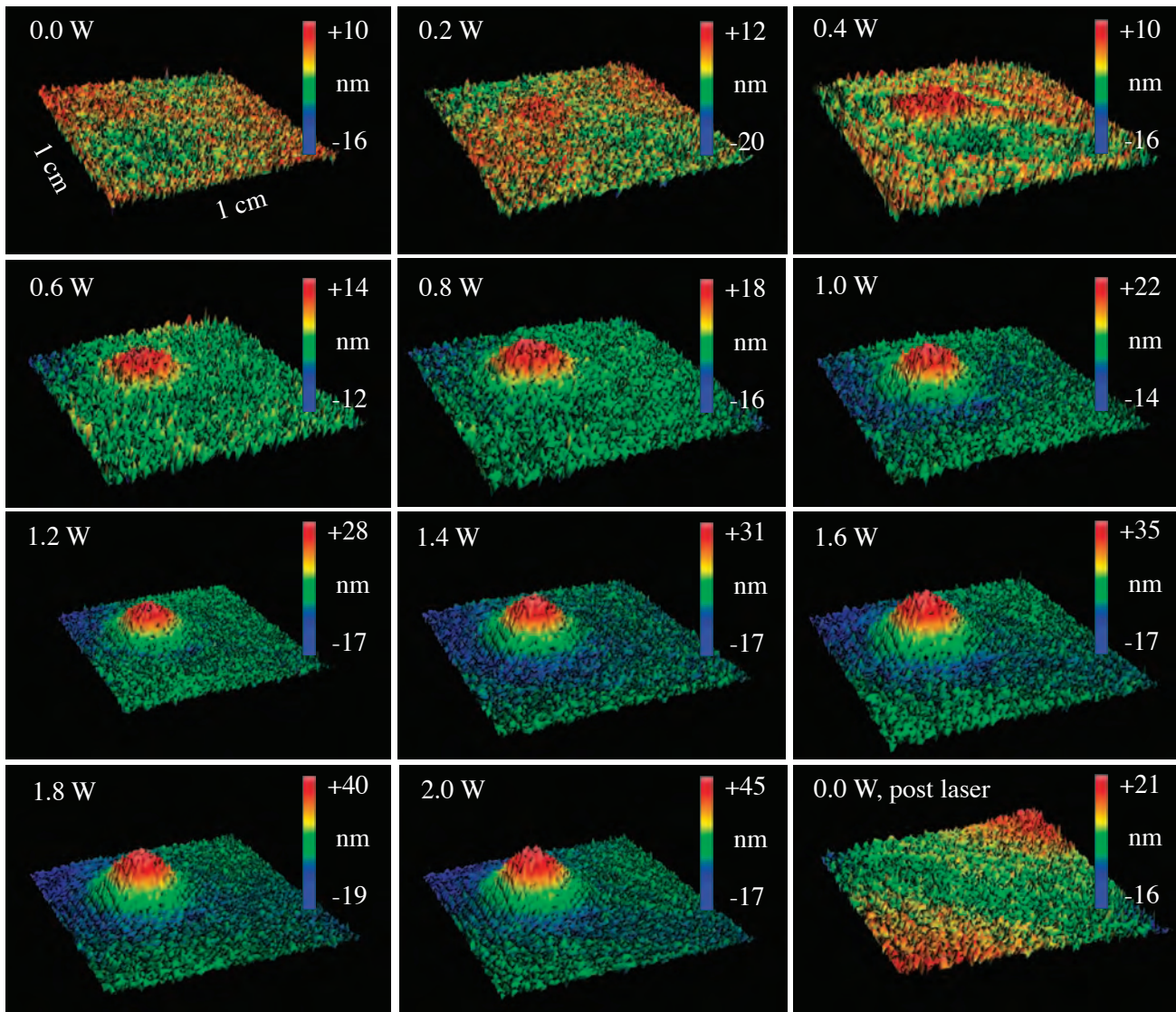
Figure 6. Interferometric images taken at 0.2 W intervals showing the aluminum-coated continuous facesheet DM's response as the laser power is ramped from 0 to 2 W . The final image shows the surface profile 1 minute after the laser power was turned off from 2 Watts. The 3.5 mm laser beam is centered on the region specified in Fig. 5.

b) perform closed loop control of the DM, or

c) monitor the DM surface during the long term test, in which the maximum 2 W was held on the DM for 7 continuous hours.

Fig. 6 shows the response of the continuous-facesheet aluminum-coated to increasing laser power (left to right) for the beam location as depicted in Fig. 5. All measurements are relative to the surface of the DM with no incident laser light. The first image is 2 consecutive measurements used to show the error of the system (RMS = 1.4 nm surface). At 200 mW there is a slightly detectable surface bulge from the laser spot. The surface bulge from spot heating continues to increase as the laser power increases, reaching a maximum of 16 nm rms surface at 2 Watts. When the laser is shuttered (returns to zero Watts with out ramping down in power) the DM surface returns to its initial shape faster than
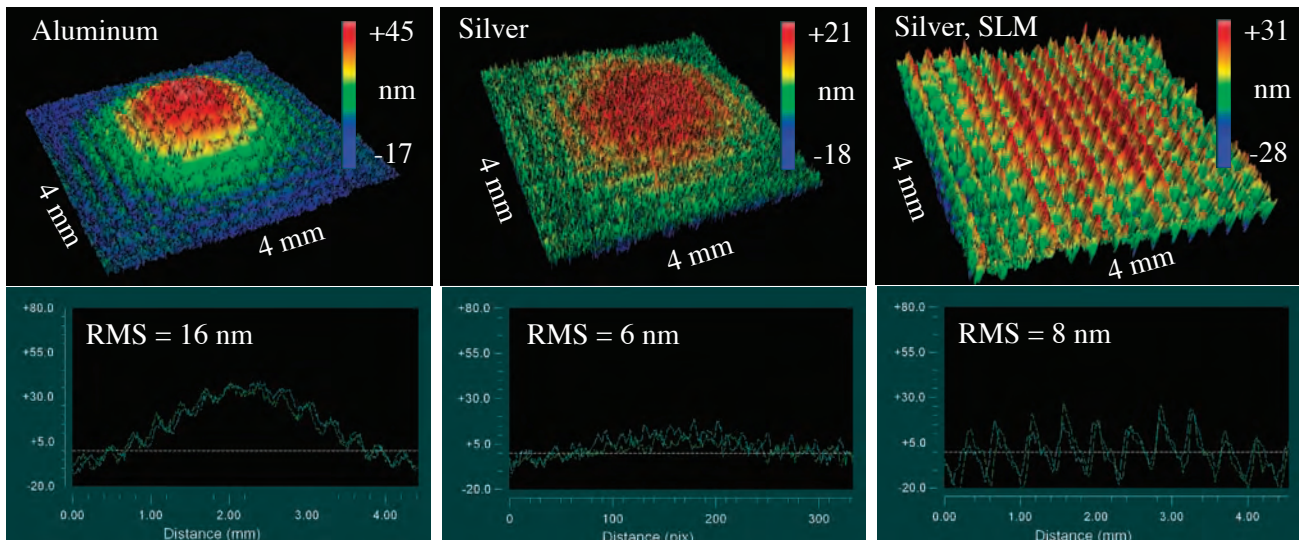
Figure 7. Resonpse of the aluminun-coated (left), silver-coated continuous-facesheet (middle), and silver-coated SLM (right), to the 3.5 mm beam at 2 Watts. With the reflectivity of silver being much greater at the laser's wavelength, there is less thermal heating and thus a much smaller surface bulge for the silver-caoted DMs.

the sampling rate of the interferometer (~ 10 seconds) with an rms figure of 1.5 nm surface (final figure at 0 W, post laser) .

A closer look at the response of the aluminum-coated DM (Fig. 7, left) to 2 Watts shows that energy from the 3.5 mm beam induces surface deformation at spatial frequencies on the order of the actuator spacing up to the beam diameter. The response of the silver-coated continuous-facesheet and SLM DMs to the same conditions are shown in Fig. 7 middle and right respectively. The incident power has much less of an effect on the silver-coated mirrors as can be seen in the corresponding x and y lineouts. This is due to the reflectivity of silver (R=96.5%)
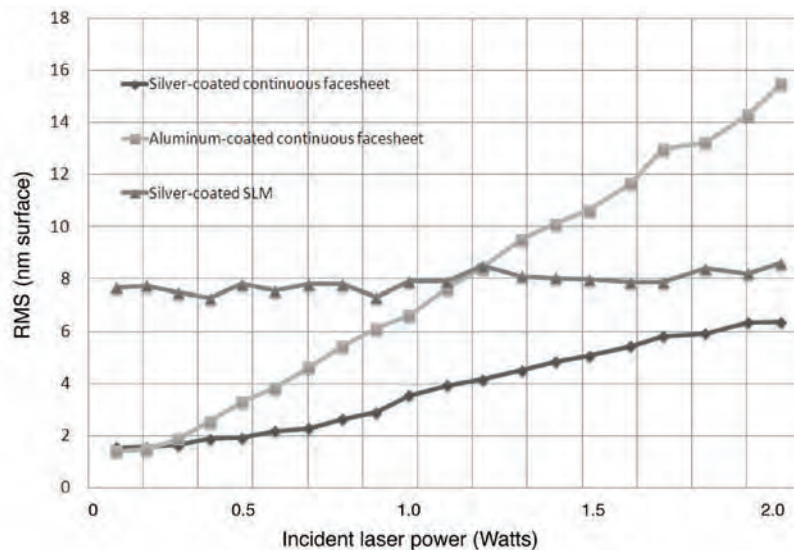

Figure 8. RMS surface measurements for the three mirrors as the laser is ramped from 0.1 to the maximum 2 Watts. The higher reflectivity of silver as compared to aluminum (96.5 % vs. 91% at λ=532 nm) reduces the amount of spot heating and energy that creates the observed surface bulge.

being greater than aluminum (R=91%). These reflectivity values are both specified for 532 nm wavelength laser light. The silver-coated continuous-facesheet DM responds by only 6 nm rms and at spatial frequencies of the order of the laser spot. Whereas the surface bulge is upward for the continuous mirrors, the SLM surface response is in the opposite direction and is observed to only occur for individual actuators. Fig. 8 shows the rms surface figures for the three DMs as a function of the increasing laser power.

Fig. 9 compares the percent difference between the input power (measured just before the DM) and the output power (measured just after each DM) as the laser was ramped to its maximum. Power meter measurements were recorded with the 3.5 mm beam. The SLM has a > 98% fill factor, so roughly 2 % of the light will be lost to the spacings between segments. The continuous-facesheet DMs have a > 99.6 % fill factor (not 100 % because of etch holes). However, these characteristics, along with the relative reflectivities, do not account for all of the observed power absorbed, and it is believed that some of the light is scattered off the DM to regions outside the detector. Whether or not the amount of light that is scattered is equivalent to the discrepancy observed in the Fig. 10 is still under investigation. The Newport power meter begins to saturate at higher power levels, explaining why the amount of power absorbed for each DM appears to decrease at higher power levels.

Closed-loop control was implemented for the silver-coated continuous mirror while the laser light was incident. Fig. 9 left image shows the 1.75 mm beam incident at 2 Watts relative to the unpowered DM surface with no laser incident. Displacements of individual actuators within the beam footprint were calculated relative to a reference region, and then were converted to voltages. These voltages were then applied to the individual actuators and are shown to remove the induced surface bulge from spot heating — Fig. 9 middle image. The voltages commanded to the DM are shown in Fig. 11. Eighty five percent of the Gaussian beam power is contained within ~ 1 mm of the beams diameter. This corresponds to roughly 3 actuators across (pitch = 300 um) and so a higher voltage must be applied to these actuators to return the surface to its initial position.
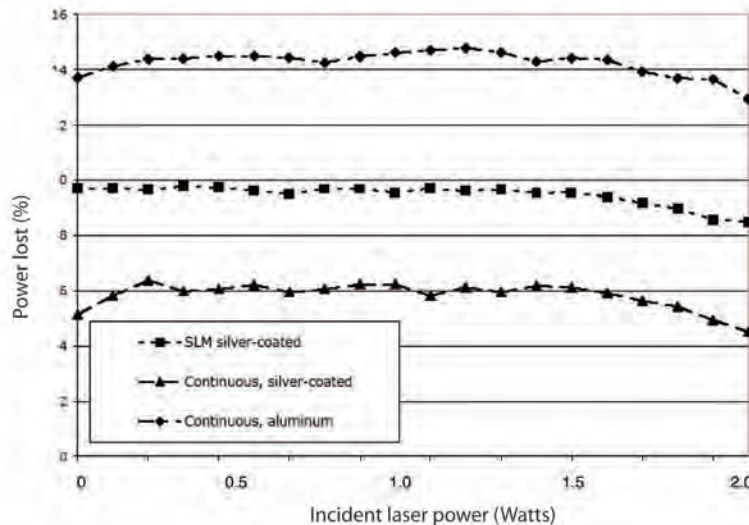

Figure 9. Comparison of the percent difference in power meter measurements before and after for the three deformable mirrors as the laser is ramped to its maximum power. The Newport power meter begins to saturate at higher power settings, explaining why the graphs all trend downward in this region.
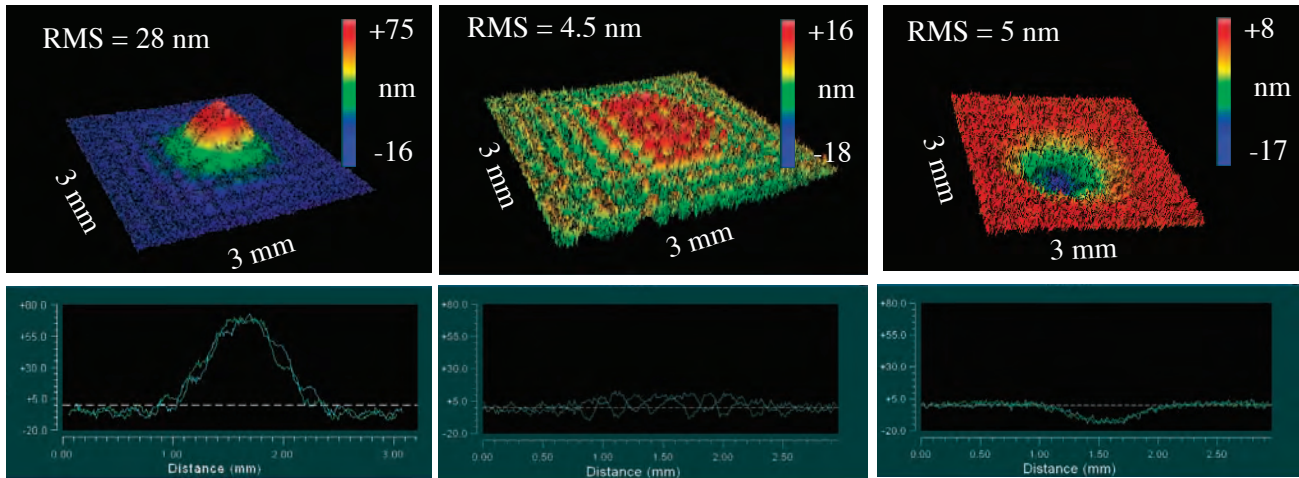
Figure 10. The silver-coated continuous-facesheet DM: Left) Response to the 1.7 mm beam at 2 Watts with no voltage applied to the DM. Middle) Applied closed-loop voltages remove the laser induced low spatial frequency bulge. Right) The mirrors surface immediately after the 1.7 mm beam was turned off (note: before the laser was turned off, the closed-loop voltages were reset to zero volts). This surface depression was only detected for the case in which the 1.7 mm beam was incident. Continuous monitoring revealed that the mirror surface did return to its original position roughly an hour later.

However, the corresponding lineout shows the that the effects of the optical power are still present at spatial frequencies of the actuator pitch.

A peculiar event takes place (Fig. 10, right) when, and all of the actuators are back to zero volts, the laser is shuttered off. The image on the right in Figure 10 shows this result, as recorded roughly 10 seconds after the laser was shuttered. The surface of the DM is observed to deflect inward by ~ 15 nm. Continuous measurements revealed the surface did return to its original position about an hour later with no loss in functionality or permanent damage. This behavior was

7	8	8	6	5
12	25	34	28	8
12	28	35	34	11
12	26	34	26	10
8	10	12	11	10

Figure 11. The closed-loop voltages used to remove the induced surface bulge caused by the 1.75 mm beam at 2 Watts. The FWHM of the Gaussian beam was measured to be ~ 1 mm. No voltages were applied to the surrounding actuators.

observed only when the 1.75 mm beam diameter was incident on the continuous and SLM silver-coated DMs. The 1.75 mm beam was never incident on the aluminum-coated DM. For cases in which the 3.5 mm beam was incident the surface of the DM returned to its initial shape faster than the ~ 10 second resolution of the Zygo interferometer setup.

For operations on-sky, the DM must be able to withstand the optical power loading for several, often continuous hours. To this end, the percent of power lost was monitored for 7 periods on two consecutive days in which the 2 Watt, 3.5 mm beam was incident for 7 continuous hours on the continuous-facesheet silver coated DM. The beam was centered on the same location as was used in previous tests, and the surface and power meter measurements were recorded every half hour. The percentage of power lost after the DM as compared with the incident power is shown in Fig. 12. The average and standard deviation for the test performed July 16 is 6.3 % and 0.4%. For July 17, these values are 6.8% and 0.2% respectively.
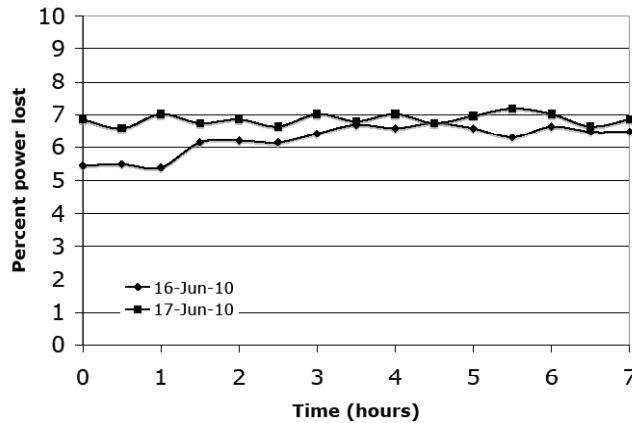
Figure 12. Two consecutive days with the 3.5 mm beam at maximum power incident on the silver-coated continuous-facesheet DM.

4. CONCLUSIONS

High-power incident laser-light tests have been performed on three Boston Micromachine Corp. deformable mirrors in tests designed to qualify their use to pre-corect a 10 W sodium laser used for laser guide star (LGS) AO. Spot heating from the laser power causes the DM's surface to bulge out of plane by only 100 nm peak-to-valley max. It was shown that closed loop operation of the devices can remove the laser induced bulge for spatial frequencies equal to the laser diameter. When the 3.5 mm laser beam diameter is shuttered, the DM responds immediately and returns to its original shape. These measurements show that one could use a 15 Watt laser (typical powers as used in laser guide stars) over the full square centimeter DM aperture and expect that the surface response be limited to only 6 nm rms for a silver-coated continuous facesheet DM array. Long term tests in which the 2 Watt laser was held on the DM for 7 continuous hours over two consecutive days showed no signs of degradation. The DMs remained fully functional with no signs of permanent damage over the entire course of the tests, making them a very promising candidtate for use in laser uplink AO.

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