Shaping Light: MOEMS Deformable Mirrors for Microscopes and Telescopes

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ABSTRACT

Micromachined deformable mirrors (DMs) have enabled rapid advances in applications ranging from large telescope astronomy and free space laser communication to biological microscopy and retinal imaging over the past decade. In this talk I describe our efforts at Boston University and at Boston Micromachines Corporation to design, fabricate, and control MOEMS DMs for adaptive optics (AO) applications. Integration of the DMs in AO systems is described, along with results demonstrating unprecedented advances in resolution and contrast in microscopes and telescopes challenged by unavoidable wavefront aberrations. MEMS-DM research offers the rare opportunity to introduce technology that is both more economical and more capable than the state-of-the-art.

Keywords: Adaptive Optics, MEMS, MOEMS, Deformable Mirrors.

1. INTRODUCTION

The emerging availability of economical, high-performance MEMS DMs has begun to transform the practice of imaging through optically inhomogeneous media with telescopes and microscopes. The result has been a marked improvement in resolution, contrast, and signal-to-noise ratio in such applications, enabled by conventional and new adaptive optics techniques.

Most large ground based telescopes now employ AO as an essential and enabling tool for high-resolution imaging. The coming generation of extremely large telescopes (ELTs) will be the first to be designed with AO at the outset. Since the benefits of AO increase nonlinearly with telescope aperture, a phenomenon sometimes called D4 scaling, AO will be essential for many ELT science goals [*1, 2*]. Promising AO instruments that will require new DMs include multi-conjugate adaptive optics (MCAO), multi-object adaptive optics (MOAO), and extreme adaptive optics (ExAO) [*3-7*]. MCAO employs two or more guide stars to enable tomographic wavefront error sensing, and then two or more deformable mirrors in series to correct those errors. The result is a wider corrected field of view [*8-11*]. This technique was recently used to produce the sharpest whole-planet (Jupiter) picture ever taken from the ground. MOAO is an instrument concept that also uses multiple guide stars and multiple deformable mirrors [*8*]. However in MOAO, many DMs would be used in parallel to apply independent corrections for the turbulence-induced wavefront distortions in separate subregions of interest, allowing high-resolution imaging of small science objects distributed across a large field of view. ExAO refers to a family of planned ground-based instruments intended for observation of exoplanets using ultra high resolution DMs having thousands or tens of thousands of actuators.

AO systems pioneered for in-vivo retinal imaging and nonlinear microscopy for subsurface imaging of biological tissue have also received considerable attention in the past decade. In those applications the low cost and compact size of MEMS DMs makes AO practical. The resulting gains in molecular-scale resolution and contrast have produced notable advances in microscopy and ophthalmoscopy and have inspired substantial new research in biophotonics [*12-27*].

2. MEMS WAVEFRONT CORRECTORS

Conventional macroscale DMs, made with either piezo-bimorphs or stacked piezo-actuators are limited as high-resolution astronomical telescope wavefront correctors. Their manual assembly makes it costly and difficult to scale to devices with large actuator count, and their large mass results in complexity in integration on telescopes. Their large power requirements and bulky electronics drivers compound these limitations. Two currently active projects for high-resolution DMs will employ conventional DMs. The first, PALM 3000, is an upgrade to the Palomar AO system on the

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5.1 meter Hale telescope [*28*]. The high-resolution DM for that instrument will be a 3388 actuator DM manufactured by Northrop Xinetics, with usable stroke of ~1.2µm. Its two full height racks of drivers dissipate several kilowatts, and cable volume constraints compelled instrument designers to locate these at the Cassegrain focus, requiring liquid cooling systems. The second, a CILAS DM with ~3000 actuators is planned for use in the Thirty Meter Telescope. This device is a scale-up based on the Cilas SPHERE DM with 1377 actuators that delivered by CILAS to the European Southern Observatory in 2007. It will weigh ~400kg. Costs for such conventional DM systems have historically been of order ~$1500/actuator.

Over the past decade, our research group at Boston University (BU), in partnership with Boston Micromachines Corporation (BMC), have pioneered design, fabrication, and control of a promising new class of deformable mirrors (DMs) for adaptive optics (AO) based on microelectromechanical systems (MEMS) technology [*29-36*]. The DM architecture, illustrated in Figure 1, is based on a scalable array of parallel plate electrostatic actuators, fabricated in silicon through semiconductor batch processing. Each square actuator plate is rigidly connected to the substrate along two of its edges, and is suspended above an addressable electrode. Voltage applied to that electrode imposes an electrostatic attractive force on the electrically grounded actuator plate, causing it to bend toward the substrate in proportion to the square of applied voltage. Each actuator plate has a central post connected to a continuous or segmented mirror layer.

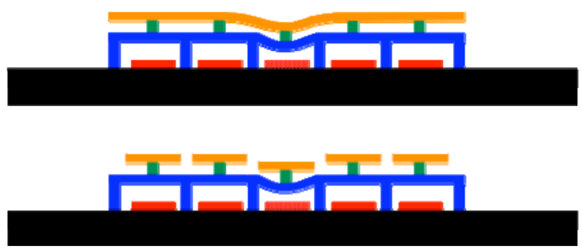

Figure 1: Schematic cross section of continuous and segmented MEMS DMs. The mirror is connected by posts to an array of electrostatic actuators. Actuator deflection is approximately proportional to the square of voltage applied to the rigid electrodes on the wafer substrate.

The design and manufacturing approaches developed in our MEMS DM research offer inherent advantages:

Design

- The actuation mechanism is repeatable to sub-nanometer precision, exhibits no hysteresis, and is unaffected by billions of cycles of operation.
- The device is compact. In some cases this can be a liability, since the Lagrange invariant imposes constraints on the practical demagnification achievable in a large telescope as the beam propagates from the primary to the optically conjugate DM. However, when the smaller MEMS DM can be tolerated (e.g. narrow filed MOAO and ExAO applications) it reduces system weight and power by more than two orders of magnitude to ~10g and ~10mW per channel, respectively.

Manufacturing

- Devices are batch produced many wafers at a time, so that while development costs are high, commercial production and replication costs are low. The MEMS DM systems (including driver) commercialized by BU/BMC cost about $150/actuator, which is one tenth that of conventional DMs.
- Multiple devices can be produced on each wafer, allowing broad parameter variation in a single batch production cycle. This accelerates research and prototyping.

MEMS-DMs offer the rare opportunity to develop technology that will be both more economical and more capable than the state-of-the-art.

In addition to higher resolution, ELT AO instruments will challenge other DM performance limits, with demands for larger stroke, nanometer-scale open loop control repeatability, and flawless actuator arrays. MEMS DM technology is particularly compelling for the latter two. MOAO will require open loop control of the DM since corrections made by the DM are not accessible to the wavefront sensor. That makes it important that the DM can be shaped to the required precision in a single step, something that is difficult or impossible to do using conventional DMs but achievable with MEMS. We recently implemented a computationally simple and inherently fast open loop control algorithm on a BU 140 actuator DM. Shapes at the limit of achievable mirror spatial frequencies were achieved with less than 15nm RMS error [*37*]. Others have also implemented open loop AO control with BU/BMC mirrors, demonstrating comparable results [*38-40*]. That open loop control architecture and the BU/BMC DM was demonstrated in the first civilian use of MEMS-based astronomical AO in the Visible Light Laser Guidestar Experiments (ViLLaGEs) led by Gavel in the past year [*41, 42*]. That work will be advanced by a recently awarded NSF MRI grant to Gavel, which will support integration of a 1020 actuator BMC DM on the Shane telescope AO system.

Our research effort has produced segmented and continuous mirrors with 32 to 4092 actuators, mirror apertures from 1.5mm to 26mm, and stroke from 2µm to 8µm. On the basis of this research and development, BMC now produces commercial products that include the MultiDM, with 140 actuators and a USB controlled driver, and the KiloDM and KiloSLM, continuous and segmented versions of a 1024 actuator device that features 30kHz frame rate. We have also manufactured unique DMs for laser communication applications, space-based reconnaissance applications, and biological imaging applications.

The focus of our development has been guided by astronomical science demands for additional stroke and larger numbers of actuators. Figure 2 depicts graphically the history and future plans for BU MEMS DMs with respect to those critical parameters. It is important to note that the peak values obtained in stroke and actuator count have not been obtained simultaneously. The largest stroke DMs (8µm) were manufactured on 140 actuator devices, while the largest actuator count devices (4092) featured 3.5µm stroke.

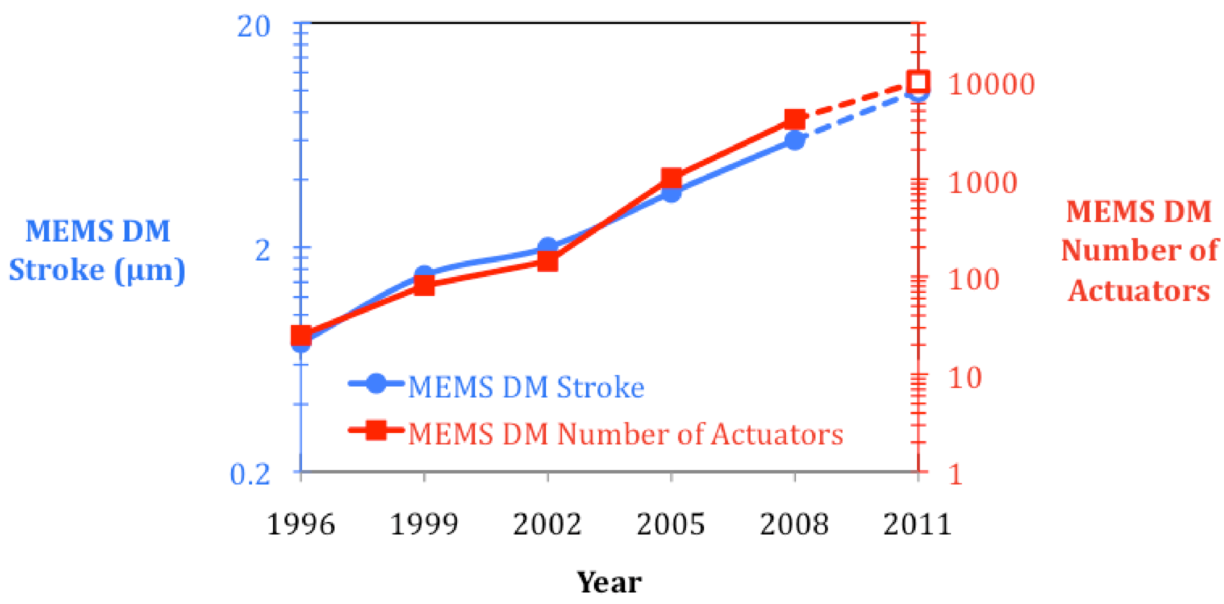

Figure 2: A history of DM peak achievable stroke and actuator count for the MEMS DMs pioneered at BU. Data correspond to fully functional deformable mirror devices with >99% working actuators (100% for devices with 1024 or fewer actuators) and optical surface quality. Results for 2011 are projected.

Measurements made on 1020 actuator MEMS DMs by the UCSC-LAO demonstrated sub-nanometer repeatability, sub-nanometer stability, and sub-nanometer hysteresis over a wide range of operating conditions[*4*]. These characteristics, are unachievable using conventional DMs and might enable unprecedented AO instrumentation. With closed loop control, the DM has been flattened in the LAO testbed to within a 0.54nm in its controllable band of spatial frequencies (and 13nm RMS overall).

3. MEMS DM APPLICATIONS

Based on heritage device designs and process science developed at BU and BMC, we recently produced a 4092 actuator 26mm aperture MEMS-DM for GPI, a new planet imaging instrument [*32, 43, 44*]. An engineering grade mirror, the first of its kind, has been delivered and is being evaluated. A science grade mirror will be delivered early in 2010. Figure 3 illustrates some preliminary results from the engineering grade mirror produced for GPI.

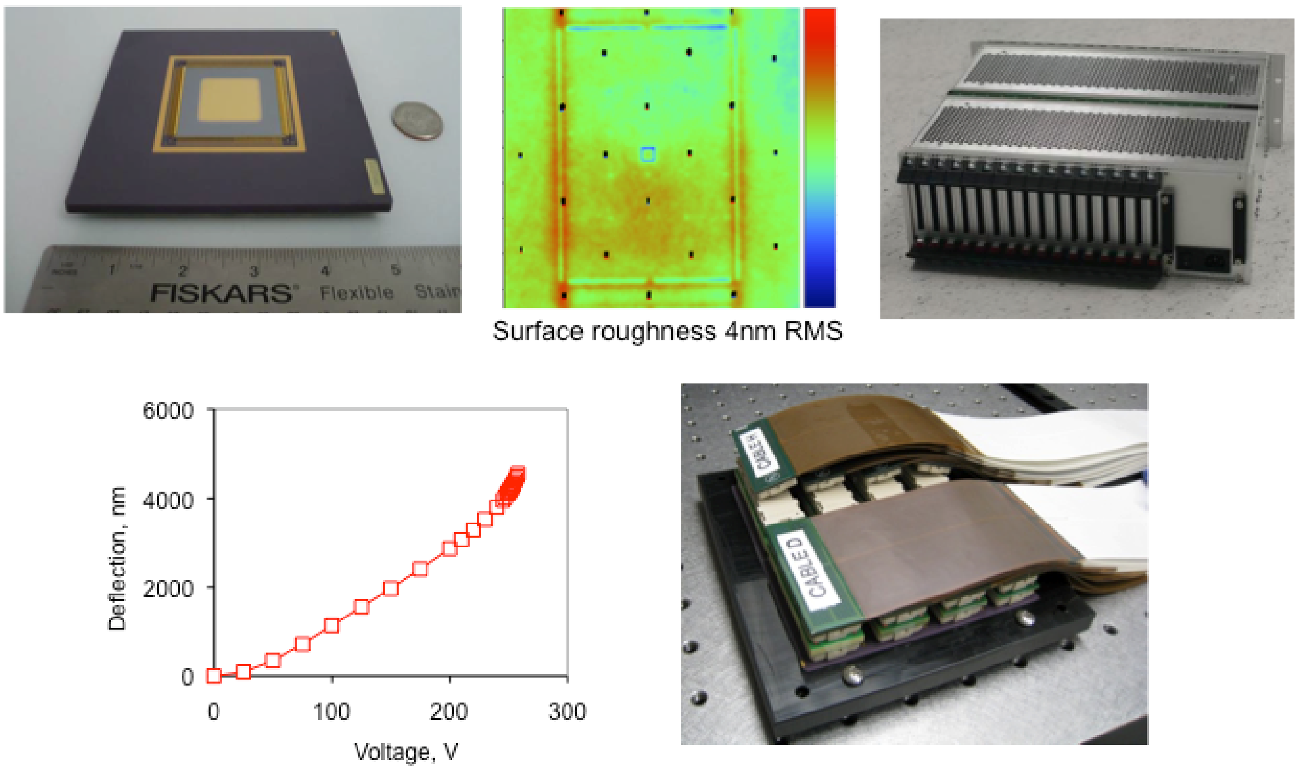

Figure 3: Engineering grade 4092 actuator MEMS DM. Clockwise from top left: Photo of the DM in its package; interferometrically measured small scale surface flatness ~4nm rms; Electronics driver; Back side of package, with eight 512-wire ribbon cables; Measured voltage vs. deflection curve.

The compact ceramic package strains the boundaries achievable wire-bonding, with wire bond leads individually attached through four peripheral rows of bond pads. Aside from a relatively large (700nm RMS) spherical non-flatness on the DM due to unexpected wafer bow, the device achieved target specifications. Local surface flatness was about 4nm RMS over a central 500µm span, and achievable stroke exceeded 4µm. Interactuator stroke exceeded 1µm. Actuator yield exceeded 99%.

BU and BMC collaborated recently on a project to deliver advanced DMs for space-based astronomical imaging supported by NASA JPL [*36, 45, 46*]. That work involved development of a segmented tip-tilt-piston mirror for a visible nulling coronagraph envisioned as part of the Terrestrial Planet Finder (TPF) program. Specifications for the mirror required advances in both design and fabrication processes, to achieve 5nm RMS flatness on the segments and to ensure less than 2nm bending of the 600µm diameter segments during tilt actuation. The innovative design included a flexure at the base of each of the three attachment posts connected to each mirror segment, and a 15µm thick post-polished silicon layer for the mirror, grown in a new epitaxial deposition process that was co-developed with a MEMS foundry. The device was delivered to JPL this year. It was successfully tested at JPL's High Contrast Imaging Testbed, and plans are underway to produce an upgraded DM with 1027 segments (3071 actuators).

In a recent initiative supported by the National Science Foundation's Center for Adaptive Optics and by a National Institutes of Health Bioengineering Research Partnership, a team of scientists produced more than a half dozen variations of retinal imaging instruments that are AO-compensated for aberrations of the eye. These include both scanning laser ophthalmoscopes (SLO) and optical coherence tomography (OCT) systems, and they have resulted in the sharpest images of microscale features in the living retina ever obtained [*12-27*]. AO has proved to be essential for high-resolution, high-contrast retinal imaging, enabled in these instruments by BMC's 140 actuator MultiDMs. The results might have significant impact on research associated with major retinal diseases and leading causes of blindness, including diabetic retinopathy, age related macular degeneration and glaucoma. In addition to other advantages already discussed, MEMS DMs are attractive in this application because their aperture diameter is closely matched to that of the eye's pupil. AO systems enabled by the BMC MEMS DM have been used for imaging photoreceptors, retinal vasculature, and blood flow velocity in foveal capillaries, and subsurface cell structure in the retina. Our group, with colleagues from LLNL, won two R&D 100 Awards for retinal AO technology: one in 2003 for a MEMS-based adaptive optics phoropter (MAOP), and one in 2007 for an adaptive optics scanning laser ophthalmoscope (MAOSLO).

In addition to retinal imaging, the MEMS DMs have had an impact on high-resolution bio-microscopy research, particularly in confocal, two-photon, and structured illumination microscopy for imaging subsurface tissue microstructures [*47-54*]. Based on one wide field microscope concept demonstrated using our DM, the first commercially available AO-enabled microscope was introduced by Thorlabs Corporation in 2008. Thorlabs now also offers catalog sale of an AO kit with the MultiDM and a Thorlabs wavefront sensor.

A final market sector for our MEMS DMs is laser beam communication and defense laser control systems. In a groundbreaking study conducted by colleagues at Lawrence Livermore National Laboratory in the California desert using a 1024 actuator DM, it was demonstrated that our DMs could compensate beam path aberrations in a single iteration over a 1km path using holographic control [*55-57*]. Significant development of laser communication systems by US defense contractors using BU/BMC mirrors has followed.

4. ACKNOWLEDGEMENTS

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