

ADAPTIVE IMAGING

MEMS deformable mirrors

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Microelectromechanical systems (MEMS) technology has allowed the realization of cost-effective, high-performance deformable mirrors for adaptive-optics-enhanced imaging.

The idea of using an array of actuators to change the shape of a mirror dates back to the second century AD, when Archimedes planned to destroy enemy ships using a solar heat ray. In his description, the shaped mirror was composed of an array of polished metal plates and the actuators were a group of Greek citizens who simultaneously aligned their mirrors such that the cumulative reflected sunlight converged to a common focal point on an enemy vessel, setting it aflame.

In modern times, more credible accounts of active light shaping date back to the invention of the eidophor projector in 1943 by Fritz Fischer, a scientist at the Swiss Federal Institute of Technology. The eidophor used electrostatic charge to locally deform an oil film on a mirror, thereby redirecting incident light for the earliest television projectors. It was this invention that inspired the astronomer Horace Babcock to dream up the concept of adaptive optics (AO), in which a dynamically reshaped mirror located in a plane conjugate to a telescope's primary mirror could be used to compensate for the blurring effects of the turbulent atmosphere between the telescope and the stars. The result, he predicted, would be a substantial increase in image resolution. The earliest deformable mirrors (DMs) developed to test Babcock's idea were made of metal-coated glass plates bonded to an underlying array of piezoelectric actuators. Although expensive and challenging to fabricate, these devices revolutionized astronomy by delivering Babcock's promise of increased telescopic resolution. By the early 1990s, such DMs and AO systems had proved invaluable in large ground-based telescopes.

In 1991, an important body of work on AO was declassified by the US Department of Defense, leading to a resurgence of interest in the field. Around that time, another technology that was emerging rapidly was microelectromechanical systems (MEMS) — tiny sensors and actuators fabricated from silicon wafers using thin-film processing that can feature flexible or moving parts. The manufacturing of MEMS devices entails three sequential steps: depositing a thin film, patterning the film with a temporary mask,

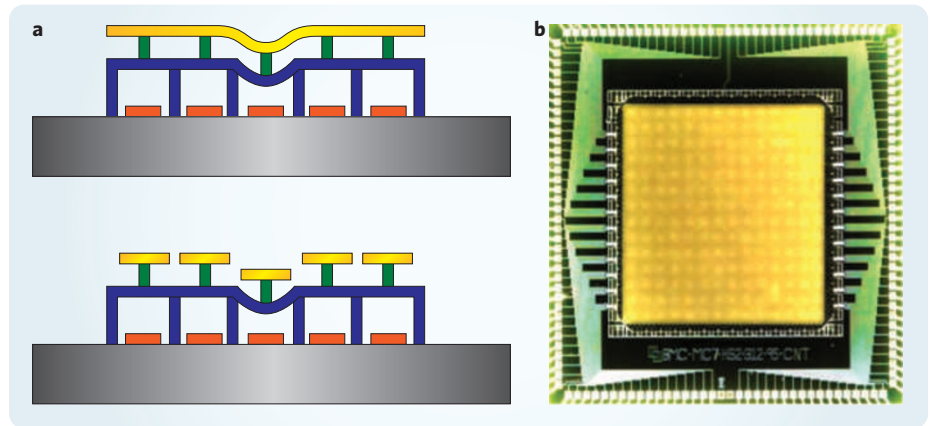


Figure 1 | Design of MEMS DMs. **a**, Cross-section of continuous (upper) and segmented (lower) MEMS DMs. A metal-coated thin-film mirror (gold) is attached by silicon posts (green) to an array of locally anchored compliant electrostatic actuator membranes (blue). Actuator deflection is controlled by applying independent voltages to an array of rigid silicon actuator electrodes (red) on the wafer substrate (black). Electrostatic attraction between the energized actuator electrodes and the electrically grounded actuator membrane deflects the actuators precisely and repeatably, thereby shaping the mirror. All structural elements are silicon. **b**, Photograph of a fabricated DM with 140 active actuators (and two inactive buffer rings) supporting a continuous DM.

and then etching the film through the mask. This cycle is repeated until the full multilayer structure is produced. Deposited films alternate between those that are structural (polycrystalline silicon, for example) and those intended to be sacrificial (such as phosphosilicate glass). A final production step is to dissolve all of the sacrificial glass layers with a wet etch in hydrofluoric acid, yielding a released, fully assembled silicon device.

In 1994, researchers at Boston University in the USA received a grant from the Defense Advanced Research Projects Agency (DARPA) to develop MEMS DMs for AO applications. The goal was to find an alternative to the expensive hand-assembled macroscale DMs that at the time represented the state-of-the-art in wavefront correction. The plan was to use the first US MEMS 'foundry' (also funded by DARPA) for this task. This approach rapidly led to prototypes of a family of DMs that suited convenient mass-manufacturing. Within several years the Boston University group had developed macro- and microscale DMs

in both segmented and continuous-mirror configurations. The devices used electrostatic actuation, and their architecture is illustrated in Fig. 1.

The success of this core electromechanical design and manufacturing approach for MEMS DMs led to devices that were in demand by researchers worldwide — not only those at Boston University. In 1999, faculty and students at Boston University spun out a company — Boston Micromachines Corporation (BMC) — to make DMs commercially available. Since then, BMC's successful family of products has been produced in continuous collaboration with academic researchers and students from Boston University. The engineering and scientific goals for the development of MEMS DMs were substantially influenced by the creation of the Science and Technology Center for Adaptive Optics, sponsored by the National Science Foundation, in 1999.

Driven by demand, research efforts at BMC have produced segmented and continuous mirrors comprising 32–4,092

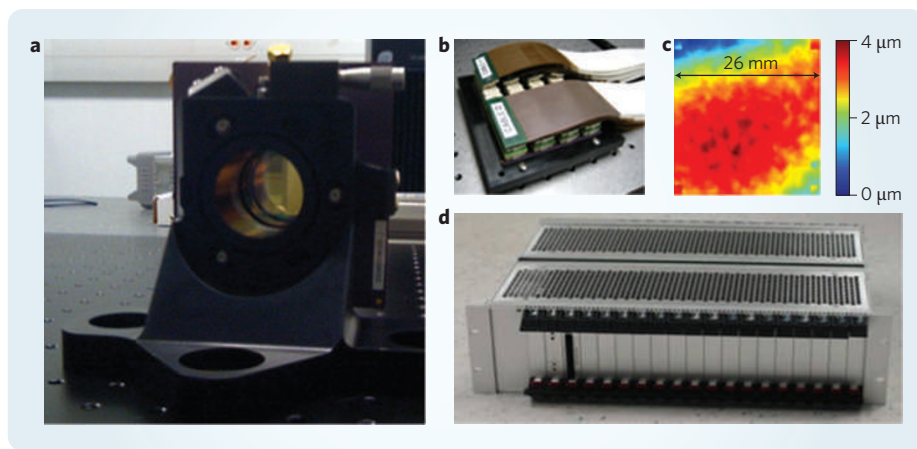


Figure 2 | BMC's 4,092-actuator MEMS DM for the Gemini Planet Imager. **a**, Photo of the DM in its package. **b**, Rear view of ceramic package and ribbon cables. **c**, Reference test shape for control tests, comprising unpowered mirror topography superimposed with $1\ \mu\text{m}$ peak-to-valley Kolmogorov phase error. Residual error for the corrected shape measured interferometrically across the full aperture of the DM was $\sim 13\ \text{nm}$ r.m.s. **d**, Driver system in a size-3U chassis.

actuators, mirror apertures of 1.5–26 mm in diameter and actuator stroke (maximum linear extension) in the range of 2–8 μm . BMC products in widespread commercial use include the MultiDM, which includes 140 actuators, and the KiloDM and KiloSLM, which are continuous and segmented versions of a 1,020-actuator device. BMC's most recent development is the 4KDM, which has 4,092 actuators and 4 μm maximum stroke. All systems come with drivers and software capable of frame rates ranging from several kilohertz to several tens of kilohertz.

MEMS DM devices bring a number of inherent benefits in their design and manufacturing processes. In terms of design, MEMS DM devices are scalable; increasing the size and spatial resolution of a DM is achieved by adding duplicate lithographic mask features. MEMS DMs are also mechanically stiff and lightweight, allowing their bandwidths to be controlled over tens of kilohertz. The non-contact electrostatic actuation mechanism is repeatable to subnanometre precision, consumes almost no power, exhibits no hysteresis and is unaffected by trillions of operation cycles.

In terms of manufacturing, the MEMS DM production approach does not call for exotic materials or manufacturing tolerances: it can exploit a MEMS foundry and begins with an optically smooth, flat and inexpensive substrate. Devices are batch-produced twenty wafers at a time, so although development costs are high, commercial production and replication costs are low. In addition, hundreds of devices can be produced on each wafer, allowing broad parameter variation in a single batch-production cycle, which accelerates research and prototyping.

Perhaps the most important benefit, however, is cost. MEMS DM systems cost almost an order of magnitude less than the technology they replace. This economic advantage has catalysed rapid growth in the field of AO, in both astronomy and other imaging applications in which aberration compensation is critical, such as improved *in vivo* retinal imaging systems and the subsurface imaging of biological tissue.

ASTRONOMICAL APPLICATIONS

Over the past decade, AO has become indispensable as a means of compensating for aberrations introduced by atmospheric turbulence in large ground-based telescopes. The resulting gains in resolution are especially important in narrow-field imaging with large telescopes, and have led to exciting recent advances in the observation of exoplanets (planets outside the Solar System), the characterization of planetary rings and atmospheres, and studies of galactic structure. AO will become increasingly important for the coming generation of extremely large telescopes, as its benefits increase nonlinearly with telescope aperture.

'Extreme' AO — the direct detection and characterization of exoplanets through coronagraphic imaging or spectroscopy combined with high-performance AO — is a key driver for the development of advanced MEMS DMs. BMC recently produced a 4,092-actuator, 26 mm aperture, 4 μm stroke MEMS DM for a new planet-imaging instrument known as the Gemini Planet Imager (Fig. 2).

BMC also produced the first MEMS DMs to be used in civilian astronomical AO, in a project known as the MEMS-AO/Visible

Light Laser Guidestar Experiments, led by Don Gavel, director of the University of California Santa Cruz Laboratory for Adaptive Optics (LAO). This experiment represents a pioneering effort to integrate MEMS DMs in an open-loop AO control system for on-sky observation. Measurements made using 1,020-actuator MEMS DMs at LAO demonstrated subnanometre repeatability, stability and hysteresis over a wide range of operating conditions. With closed-loop control, the DM in the LAO test-bed has been flattened to within 0.54 nm of its controllable band of spatial frequencies, with an overall root-mean-squared (r.m.s.) flatness of 13 nm.

BMC also developed advanced DMs for space-based astronomical imaging, supported by the NASA Jet Propulsion Laboratory (JPL). This involved the development of a segmented tip-tilt piston mirror to produce visible nulling coronagraphs for the Terrestrial Planet Finder programme. Meeting the mirror specifications required advances in both the design and fabrication processes, particularly to achieve an r.m.s. flatness of 5 nm on the segments and to ensure less than 2 nm bending over the 600 μm 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 15- μm -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 in 2009 (Fig. 3) and successfully tested at the Visible Nulling Coronagraph Testbed, following which a contract was established with NASA to produce an upgraded DM with 1,021 segments (3,063 actuators) in 2010, along with a multiplexed ultralow-power driver. In a second space-based DM project for astronomical imaging, BMC collaborated with Supriya Chakrabarti from Boston University's Center for Space Physics to produce a 1,020-actuator DM for a NASA sounding rocket project.

RETINAL IMAGING

In vivo retinal imaging using AO-enhanced ophthalmoscopes was a key driver for the development of MEMS DMs. The motivation was straightforward: uncompensated aberrations of the eye generally prevent ophthalmoscopic instruments from resolving cellular structures of the retina. The diffraction limit for the optics in the eye would allow cellular resolution, however, if such aberrations could be corrected. A pioneering effort by David Williams' research group at the University of Rochester demonstrated closed-loop AO in 1997,

yielding substantial improvements in image quality and the first clearly resolved images of cone photoreceptors. A decade of subsequent research by many groups yielded numerous additional advances, including the integration of AO into confocal scanning laser ophthalmoscopy and optical coherence tomography instruments, and the development of MEMS DMs designed specifically for use in retinal imaging AO. The capacity of confocal AO systems to resolve cellular and microvasculature structures has led to a rapid increase in the number of AO publications and development grants over the past decade. BMC MEMS DMs in particular have been a critical and enabling component for aberration compensation and AO in vision science instruments. BMC MultiDMs were specifically designed to compensate for aberrations of the eye, with a 4.4 mm aperture, 6 μm stroke and 140 actuators. In a recent initiative supported by the National Science Foundation through the Center for Adaptive Optics and a grant from the National Institutes of Health Bioengineering Research Partnership, a team of scientists produced more than a half-a-dozen variations of retinal imaging instruments that are AO-compensated using BMC MEMS DMs. These include both scanning laser ophthalmoscopes and optical coherence tomography systems, and have resulted in the sharpest images ever obtained of microscale features in the living retina.

In collaboration with Steven Burns at the University of Indiana, USA, BMC recently integrated a 6- μm -stroke DM into an AO laser scanning ophthalmoscope (AOSLO). The AOSLO's lateral resolution of $\sim 2\ \mu\text{m}$ enables *in vivo* high-resolution imaging of previously indiscernible retinal structures. This instrument will be used in 2011 to evaluate the clinical usefulness of enhancements in resolution, contrast and brightness when monitoring the progression of disease, as well as the effectiveness of treatments that affect cellular structures in the retina.

BIOLOGICAL MICROSCOPY

MEMS DMs are compact and inexpensive, allowing them to be easily integrated into many experimental microscopy platforms that might benefit from AO-enhanced performance. Two prominent examples are multiphoton microscopy for the subsurface imaging of biological tissue, and adaptive scanning microscopy for high-resolution, wide-field imaging.

In multiphoton microscopy for the subsurface imaging of biological tissue, image quality is affected by both scattering in the biological medium and by an index-of-refraction mismatch between the tissue and the water/oil on which the microscope

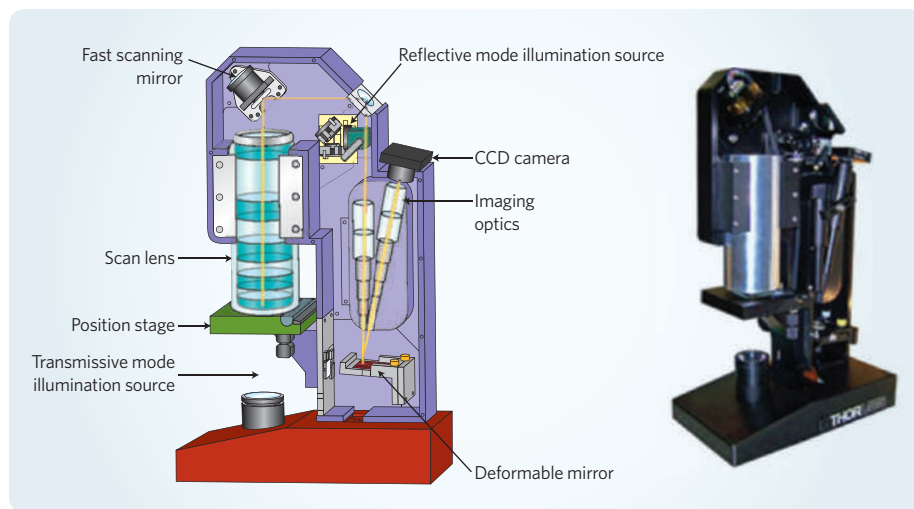


Figure 3 | Schematic (left) and photograph (right) of the ASOM — the first commercially available AO microscope — produced by Thorlabs and built using the BMC MultiDM system.

objective is optimized. In principle, AO can be used to overcome the deleterious effects (primarily spherical aberration) resulting from this index mismatch. However, multiple scattering makes it challenging to measure such aberrations. As a result, this application relies on 'sensorless' AO techniques, in which an optimization scheme iteratively reshapes the DM and then measures the resulting image quality. MEMS DMs have proved to be well-suited to this type of control because they are fast (frame rates of $>10\ \text{kHz}$) and can be shaped precisely and predictably in an open loop. Exploiting this shaping characteristic makes it possible to improve the performance of iterative AO control techniques by intelligently selecting perturbation shapes (spherical aberration, for example). Recent demonstrations of AO compensation in two-photon microscopy using BMC MEMS DMs in biological imaging, led by Charles Lin at the Massachusetts General Hospital Wellman Center for Photomedicine, have extended the useful imaging depth of this application.

Although all of the AO example applications described so far have used MEMS DMs to correct for intrinsic aberrations in the optical beam path of an imaging instrument (atmospheric turbulence, misshapen cornea/lens and heterogeneous biological tissue), it is also possible to use AO to broaden the design space for optical instruments themselves, even in the absence of sample aberrations. A prominent example is the adaptive scanning optical microscope (ASOM) developed by the Center for Automation Technology at the Rensselaer Polytechnic Institute in the USA. This instrument uses AO to replace stage scanning with beam scanning in a

high-resolution microscope that images over a wide field-of-view. Imaging such a wide field at high resolution (in pathology screening, for example) normally requires a narrow-field, high-resolution objective to be positioned above the translating stage, after which the sample itself is moved to construct a composite mosaic image. Wider field objectives are possible and have been used in lithographic applications, but making such objectives with sufficient quality to achieve diffraction-limited image quality across the field is prohibitively expensive for most applications. In the ASOM, a wide field objective is manufactured at low cost. Its aberrations at different scanning angles are measured in a calibration process and then compensated for using a MEMS DM inserted in the microscope beam path. The ASOM offers an expanded field-of-view, rapid scanning speeds, low light imaging capabilities and no specimen movement.

A final market sector for MEMS DMs is in laser beam communication and defence laser control systems. In a groundbreaking study sponsored by DARPA and led by Lawrence Livermore National Laboratory, the original 100-actuator BMC DM design was scaled up to a 1,020-actuator segmented DM that compensates for beam path aberrations in a single iteration over a horizontal path using holographic control. Significant development of laser communication systems using Boston University/BMC mirrors has followed, leveraged by support from DARPA, the US Air Force and the US Army. \square

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