

# Micro-electromechanical systems spatial light modulator development

S. Olivier<sup>a</sup>, P. Bierden<sup>b</sup>, T. Bifano<sup>c</sup>, D. Bishop<sup>d</sup>, E. Carr<sup>a,e</sup>, W. Cowan<sup>f</sup>, M. Hart<sup>g</sup>, M. Helmbrecht<sup>g</sup>, P. Krulevitch<sup>a</sup>, R. Muller<sup>g</sup>, B. Sadoulet<sup>h</sup>, O. Solgaard<sup>i</sup>, and J. Yu<sup>a</sup>

<sup>a</sup>Lawrence Livermore National Laboratory, P.O. Box 808, L-258, Livermore, CA 94551

<sup>b</sup>Boston Micromachines Corporation

<sup>c</sup>Manufacturing Engineering Department, Boston University

<sup>d</sup>Lucent Technologies

<sup>e</sup>Department of Electrical and Computer Engineering, University of California Davis

<sup>f</sup>Air Force Research Laboratory, Wright-Patterson Air Force Base

<sup>g</sup>Berkeley Sensor & Actuator Center, University of California Berkeley

<sup>h</sup>Department of Physics, University of California Berkeley

<sup>i</sup>Department of Electrical Engineering, Stanford University

## ABSTRACT

The NSF Center for Adaptive Optics (CfAO) is coordinating a five to ten year program for the development of MEMS-based spatial light modulators suitable for adaptive optics applications. Participants in this multi-disciplinary program include several partner institutions and research collaborators. The goal of this program is to produce MEMS spatial light modulators with several thousand actuators that can be used for high-resolution wavefront control applications and would benefit from low device cost, small system size, and low power requirements. We present an overview of the CfAO MEMS development plan along with details of the current program status. Piston mirror array devices that satisfy minimum application requirements have been developed, and work is continuing to enhance the piston devices, add tip-tilt functionality, extend actuator stroke, create a large array addressing platform, and develop new coating processes.

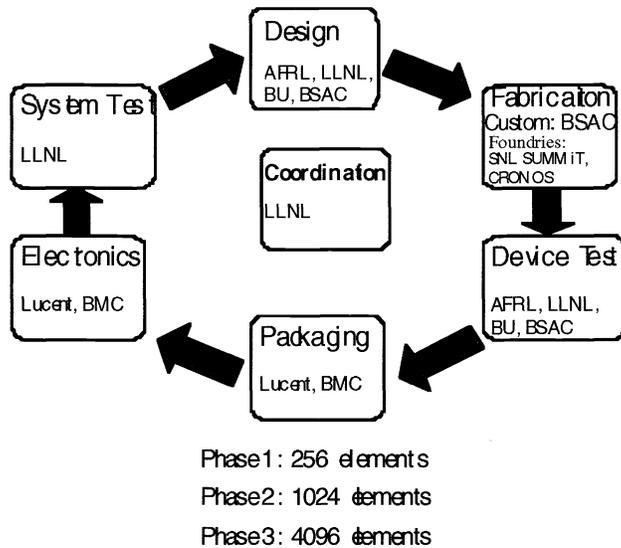
**Keywords:** adaptive optics, spatial light modulator, micro-electromechanical systems, MEMS, microfabrication

## INTRODUCTION

One of the four stated goals of the NSF Center for Adaptive Optics (CfAO – [www.ucolick.org/~cfao/](http://www.ucolick.org/~cfao/)) is to develop advanced AO systems with major new capabilities. A main thrust of this effort is focused on micro-electromechanical systems (MEMS) deformable mirror arrays, which will enable small, low cost devices with enhanced functionality. The CfAO's strategy for advancing AO microtechnology is to investigate new MEMS approaches and to foster on-going efforts with the Center's partner institutions (UC Berkeley, Lucent Technologies, Lawrence Livermore National Laboratory) and research collaborators (Air Force Research Laboratory, Boston University, UC Davis, Stanford University). A major function of the Center is to make a connection between AO end users, application requirements, and microfabrication engineers. In this paper, we discuss the details of the CfAO's MEMS development plan, and report on developments during the Center's first year.

## CfAO MEMS DEVELOPMENT PLAN

The CfAO MEMS development plan, illustrated in Fig. 1, includes three microfabrication approaches, which are being pursued in parallel. The plan is heavily leveraged from pre-existing programs at participating CfAO partner and collaborator institutions. The primary role of the CfAO has been to coordinate and focus these activities on specific technical goals relevant to the CfAO. Two promising electrostatically-actuated devices, generated at the Air Force Research Laboratory (AFRL) [1-3] and Boston University (BU) [4-5], are being pursued. These designs utilize processes at the most established surface micro-machining foundries, Sandia National Laboratory (SNL) and Cronos/JDS Uniphase. The Berkeley Sensor & Actuator Center (BSAC) is developing new designs and custom fabrication processes for next-generation devices. Packaging and drive electronics are being provided by Lucent Technologies, based on infrastructure from their optical cross-connect switching product, and by Boston Micromachines Corporation (BMC), a start-up company working with Boston University to commercialize their MEMS SLM device technology. LLNL's role is to coordinate the efforts of the various groups, provide technical support, explore technologies for risk-reduction, and test the devices.

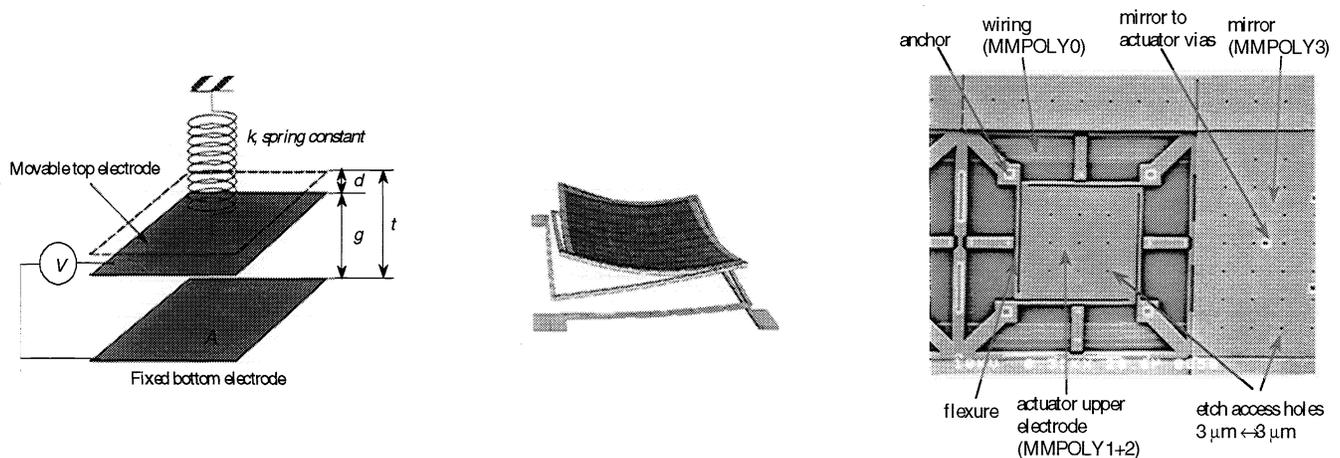


**Figure 1** – CFAO MEMS SLM primary development cycle flow chart.

The development plan consists of three phases, each with increasing number of mirror elements in the array. Evolution of the system architecture, such as integrated electronics and through-substrate electrical contacts, will be required to achieve the increased array sizes. The CFAO MEMS SLM development program is currently in the phase 1 iteration.

### MICROFABRICATION APPROACHES

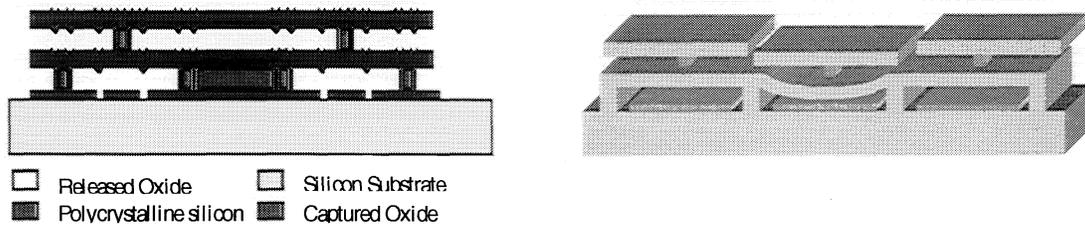
The development path based on the AFRL device design is currently in the fabrication stage at Sandia National Laboratory with a 252-element device. Fabricated devices should be available for packaging and integration with drive electronics at Lucent during the Summer of 2000, and should be ready for system testing during the Fall of 2000. A drawing of the parallel plate actuator concept and a finite element analysis schematic are shown in Figure 2 along with a cutaway view of a device designed at AFRL and fabricated at SNL. Measurements of the pixel surface quality of prototype devices fabricated in the SNL foundry using this AFRL design have yielded results of better than 20 nm pv.



**Figure 2** – Parallel plate actuator concept, finite element analysis, and cutaway view of MEMS SLM designed by AFRL and fabricated at Sandia National Laboratory. Pixel surface quality of better than 20 nm pv has been measured on prototype devices.

The development path based on the Boston University device design is currently in the system test stage with a 140-element device. LLNL received a packaged device with drive electronics mid-summer 2000 from BU, and has begun initial characterization measurements. The design of the surface micromachined layer structure and a drawing of the device concept

are shown in Figure 3. Boston Micromachines and Boston University have developed a simple post-processing technique to modify stress gradients in the mirrors [6]. After application of this technique, pixel surface quality of better than 10 nm rms has been obtained. See the paper "A micromachined deformable mirror for adaptive wavefront compensation," by T. Bifano and P. Bierden published in this proceedings for fabrication details and characterization results on these mirrors.



**Figure 3** – Schematic of layer structure and drawing of design concept for MEMS SLM designed by Boston University.

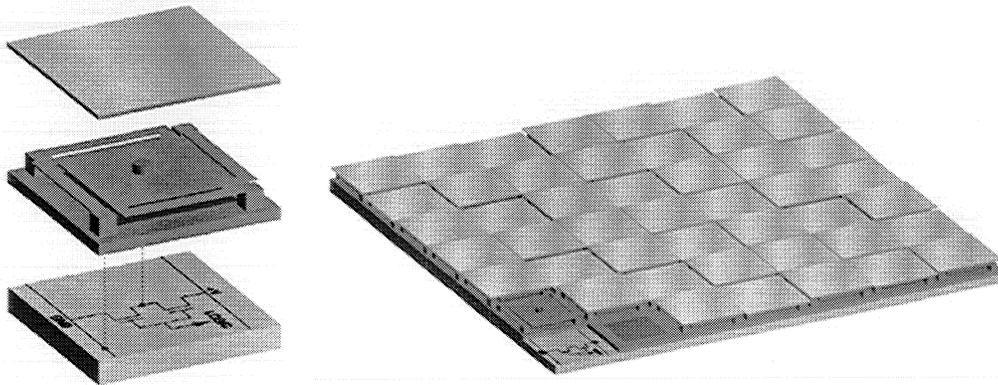
Along with the primary development cycle, the CfAO MEMS plan calls for additional activities to develop designs for high-stroke (greater than 4 microns) actuators, for addressing large-format devices (greater than 2000 controlled degrees of freedom), and for improving efficiency of piston mirror arrays by adding tip-tilt capability. High-stroke actuators are being developed at BSAC in a coordinated CfAO project. An alternative high-stroke actuator concept was developed at LLNL, but further work using this design has been postponed in favor of the mirror bonding activity described below. Devices that incorporate tip-tilt capability as well as devices with continuous surface control have been developed by Boston University. These devices will be tested along with the BU piston mirror devices later this year.

### SCALABILITY OF MIRROR ARRAY SIZE

The two surface micromachining approaches based on the AFRL and BU designs described above utilize proven manufacturing processes, and represent the lowest risk options for achieving a 1024-element array in the shortest possible time. However, in order to go beyond 1024 elements, new processing approaches may be required. The scaling limitation for the pure surface micromachining approaches is due to the necessity of making electrical connection to each pixel by means of a wire that must be run out to the edge of the device through one of a small number of available layers. These wires terminate in a bond pad to which another set of wires must be connected leading to the drive electronics located off-chip. While this topology is feasible for a 32×32 device, it becomes impractical for much larger devices. The solution is to integrate the drive electronics with the MEMS SLM device so that the drive circuitry is situated beneath each pixel and any required electrical connections between the drive circuit and the SLM pixel are made from the back of the SLM.

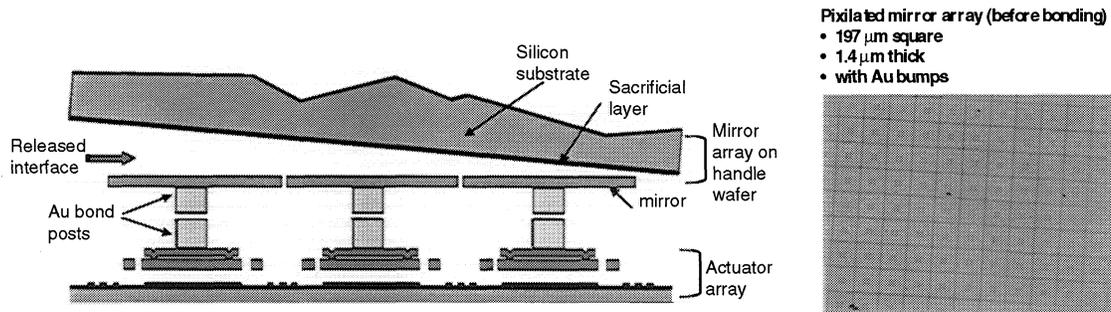
There are two general methods to accomplish the integration between the SLM and drive circuitry. The first method is to fabricate the MEMS SLM device and the drive electronics in two separate chips and then use a chip bonding technique to bring the two devices together. A similar approach is used, for example, in the fabrication of infra-red detector arrays by the Rockwell Science Center, which uses an indium bump bonding technology to reliably make electrical connection between millions of array elements and amplifier circuits. The second integration method is to fabricate the MEMS SLM directly on top of the drive circuitry. This approach has been used, for example, by Texas Instruments in the fabrication of the Digital Micromirror Device, which has been produced with over two million pixels.

LLNL and BSAC are also working on modular integration concepts in which the mirror substrate, micromachined actuators, and drive electronics are each fabricated separately and then bonded together. A conceptual drawing of this approach is shown in Figure 4. The advantage of this approach is that the mirror, actuators and drive electronics can be optimized independently, and that addressing lines and electrodes can be put under the mirrors without compromising the mirror quality. Consequently, the fabrication risks for each of the three separate structures are minimized in this approach. Moreover, the bonding of the drive electronics and the actuators can be accomplished using proven commercially available chip bonding technology.



**Figure 4** – Conceptual drawing of a MEMS SLM assembled by modular integration of separate mirror elements, micromachined actuators, and drive circuitry that are bonded together.

The main risk area for the modular integration approach is the bonding of the mirrors to the actuators with the required yield while maintaining surface quality. As part of the risk reduction activity of the CfAO MEMS SLM development program, BSAC and LLNL have been collaborating on the investigation of several different mirror-bonding techniques using several different mirror substrate materials. A conceptual schematic of one technique that uses gold bump bonding is shown in Figure 5, along with a micrograph of a mirror array with gold bumps before bonding. Silicon-on-insulator (SOI) and a proprietary LLNL tunable-stress coating are among the materials being evaluated for the mirror elements. This work will continue throughout the year.



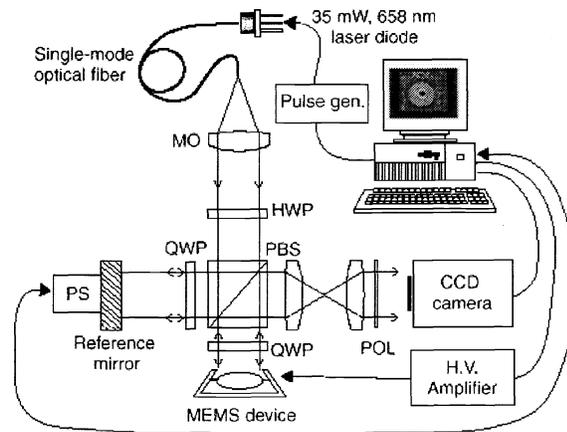
**Figure 5** – Conceptual drawing of a mirror bonding technique using gold bumps, and micrograph of mirror array with gold bumps before bonding.

## DYNAMIC DEVICE CHARACTERIZATION

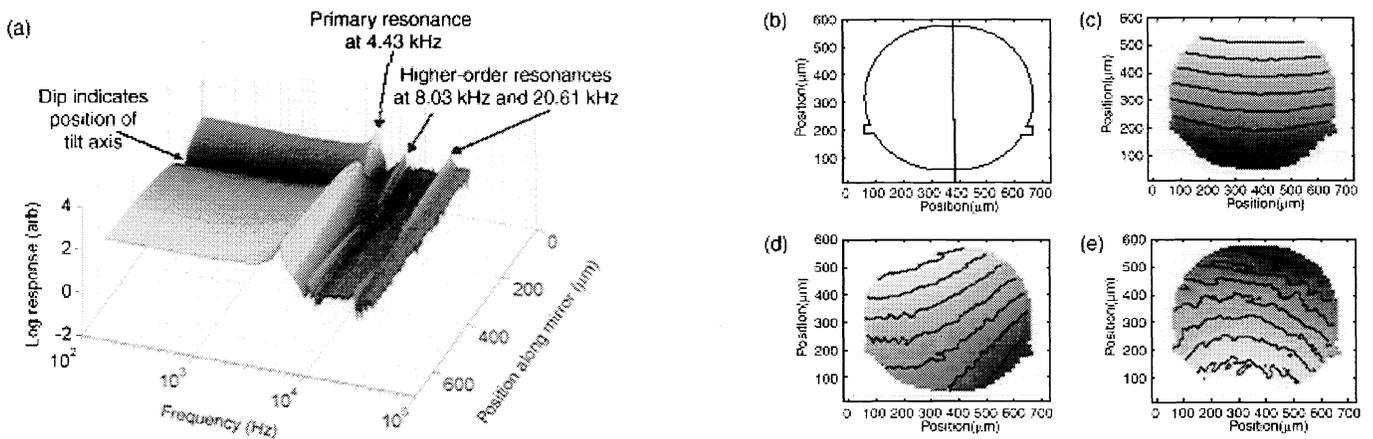
The Berkeley Sensor & Actuator Center has developed a stroboscopic interferometer to measure the position and shape of a static specimen or that of a moving specimen. The system measures periodic out-of-plane movements or in-plane movements of MEMS structures. By using microscope optics with a large numerical aperture, the system achieves a spatial in-plane resolution of  $1\mu\text{m}$ . The resolution of out-of-plane deflections is far better than  $1\mu\text{m}$ , because the out-of-plane shift is defined by phase difference of the measurement beam and a reference beam. Applying a phase shifting technique to evaluate the interferograms allows for the measurement of out-of-plane motion with nanometer accuracy.

A pulsed-laser diode with a coherence length of a few tens of microns is used as a strobe light. The length of the laser pulse defines the exposure time and, therefore, the time resolution of the system, which is 100 ns. Out-of-plane motion with a velocity of up to 1.5 m/s can be measured with the stroboscopic interferometer. The largest measurable out-of-plane deflection is fixed by the depth-of-focus of the imaging optics and by the coherence length of the illumination. The maximum measurable slope of a reflective surface depends upon the aperture of the imaging system because reflected beams need to be captured by the microscope objective. The current system has a microscope objective with a numerical aperture of  $N_a = 0.4$  (Zeiss LD Epiplan, 20x magnification). Out-of-plane deflections up to  $10\mu\text{m}$ , in-plane deflections of hundreds of

micrometers, and slope angles up to 10 degrees have been measured. The experimental set-up is shown in Fig. 6, and measurements on an oscillating mirror are shown in Fig. 7.



**Figure 6** – Experimental arrangement for the computer-controlled stroboscopic interferometer. The abbreviations used are as follows: MO – microscope objective, HWP – half-wave plate, QWP – quarter-wave plate, PS – piezoelectric stage, PBS – polarizing beamsplitter cube, POL – linear polarizer.



**Figure 7** – (a) Experimental logarithmic response for 104 separate points on the mirror surface, distributed along a line perpendicular to the tilt axis. The log(amplitude) data are plotted as a function of frequency (shown on a log scale) and lateral position. (b) Line on the mirror surface for which response data are plotted in (a). (c), (d) and (e) Modeshape estimates for resonant peaks observed at 4.43, 8.06 and 20.61 kHz respectively. Each of these three plots is a surface-height contour-map corresponding to one extreme of the motion seen at the specified frequency. The surface height scales are arbitrary. Lighter shading corresponds to larger surface-height values. The modeshape estimates were found by Fourier filtering of the measured (position, time) vectors at each point on the mirror surface. The lack of left-right symmetry in the mode seen at 8.06 kHz is the result of play in the scissor- and pin-and-staple hinges that allow the mirror and frame to be folded out of the substrate plane.

## SUMMARY AND FUTURE WORK

The NSF Center for Adaptive Optics is working with its partner institutions and research collaborators to advance the state-of-the-art in MEMS technology to produce wavefront control devices suitable for application to adaptive optics systems for

astronomy and vision sciences. The Center's plan begins with existing piston mirror array devices that satisfy minimum requirements for these applications and will then extend the development along 5 paths, including incremental improvements of the existing piston mirror arrays, addition of tip-tilt functionality, new design concepts for high stroke actuators, new design concepts for addressing large-format arrays, and new coating processes.

### ACKNOWLEDGEMENTS

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