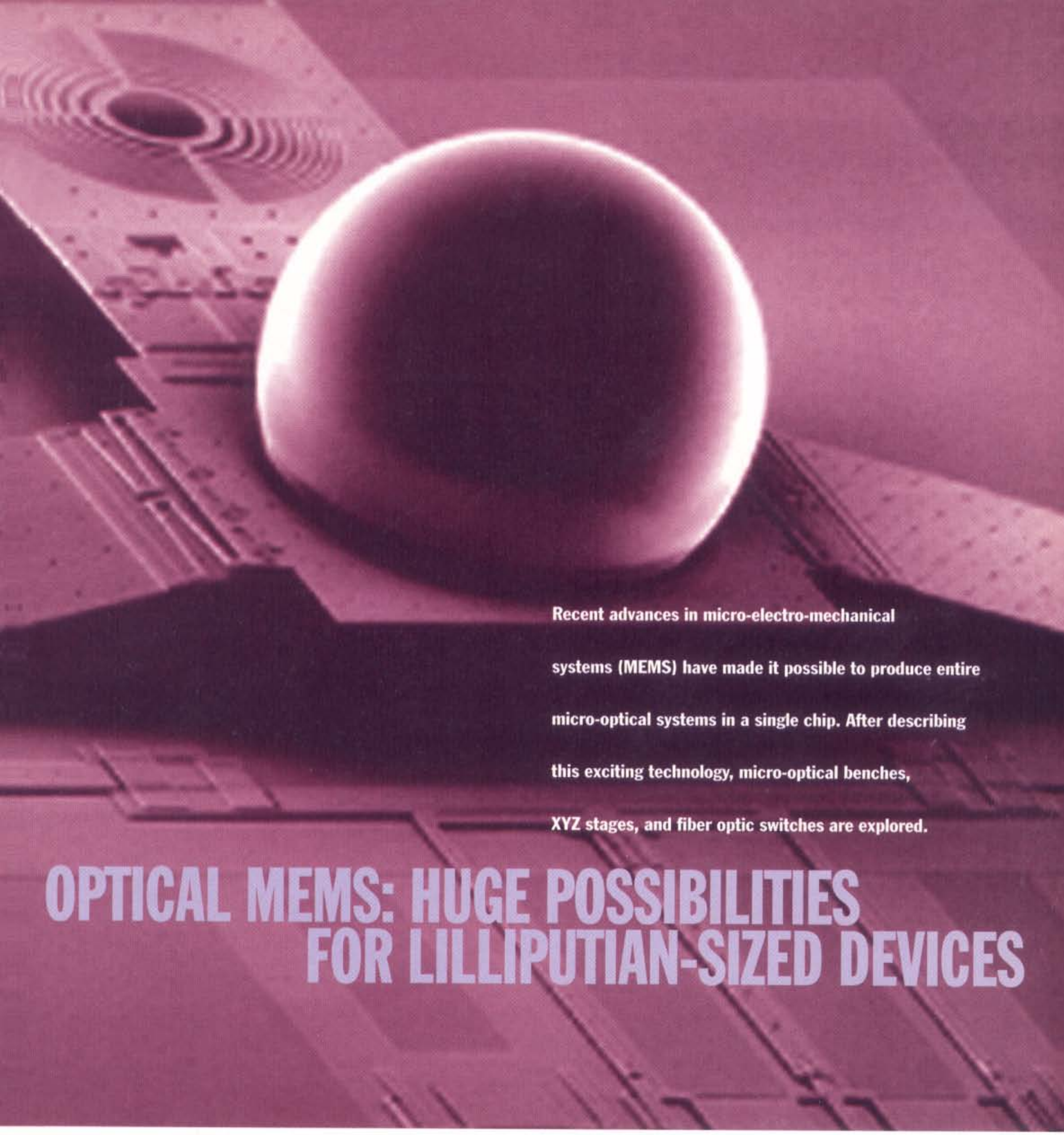

OPTICAL MEMS: HUGE POSSIBILITIES FOR LILLIPUTIAN-SIZED DEVICES

Recent advances in micro-electro-mechanical systems (MEMS) have made it possible to produce entire micro-optical systems in a single chip. After describing this exciting technology, micro-optical benches, XYZ stages, and fiber optic switches are explored.

Optomechanical devices—such as XYZ micropositioners widely used for alignment of optical systems, rotary gratings and etalons that vary the wavelength of tunable lasers, and focusing lenses in CD-ROMs that constantly move to maintain focus and tracking—are essential components of many optical systems. Unfortunately, conventional optomechanical devices are bulky, slow,

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expensive, and suffer from poor reliability. In the past few decades, there has been a great deal of research on how to replace the mechanical moving parts with electro-optic devices. Indeed electro-optic scanners and tunable filters with no moving parts have been reported. The tuning range of these devices, however, is usually small compared to their optomechanical counterparts since electro-optic or other physical effects produce only a small perturbation on refractive index. Optomechanical devices, on the other hand, can move over distances of hundreds of wavelengths or rotate over large angles.

Recent advances in micro-electro-mechanical systems (MEMS)[1] have made it possible to produce compact optomechanical structures and microactuators at low-cost, using batch-processing techniques. Movable optomechanical structures, micromotors rotating at record speeds (over a million revolutions per minute), and linear microactuators with extremely high accuracy (on the order of 10 nm) are just a few examples. MEMS technology has opened up many new possibilities for optical and optoelectronic systems, including optomechanical devices that can be monolithically integrated on a single chip. Compared with macro-scale optomechanical devices, micromechanical devices are smaller, lighter, faster (higher resonant frequencies), and more rugged. Very efficient light modulators, switches, broadly tunable lasers, detectors, and filters can now be realized. This family of new devices is called micro-opto-electro-mechanical systems (MOEMS) or, simply, optical MEMS. The applications of optical MEMS include projection and head-mounted displays, optical data storage, printing, optical scanners, switches, modulators, sensors, and optoelectronic components packaging.[2]

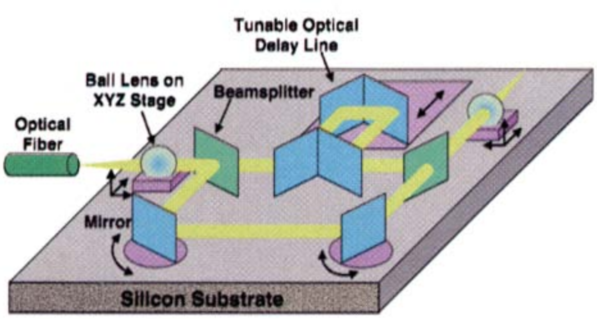

Figure 1. Schematic illustrating the concept of a FS-MOB realized by surface micromachining.

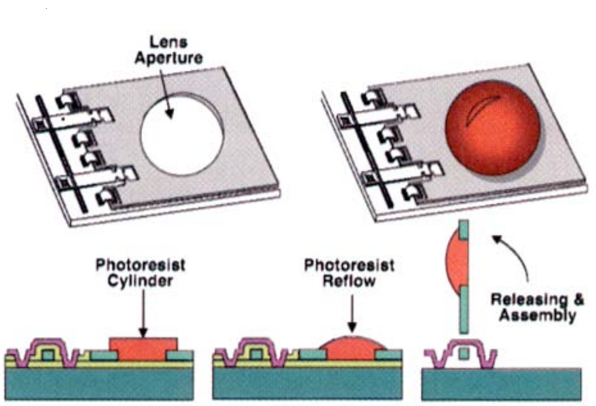

Figure 2. Fabrication process for making an out-of-plane refractive microlens.

This article provides a brief introduction to MEMS technology, discusses fabrication processes, and introduces the concept of the free-space micro-optical bench, including its basic building blocks. Two examples of optical MEMS—micro XYZ stages and MEMS fiber optic switches—are also discussed, followed by experimental results, and concluding with the impact of optical MEMS on future optical systems.

How MEMS are fabricated

MEMS technology includes both bulk and surface micromachining. In bulk micromachining, precise mechanical structures are created on silicon wafers by anisotropic etching. The etching rate of silicon in (111) crystal planes is much slower than in (100) or (110) planes in etchants such as EDP, KOH, or TMAH. As a result, bulk micromachining can create very precise V-grooves, pyramidal pits, and cavities. This is a very mature technology, and the optics community has long been using V-grooves for positioning or aligning optical fibers and micro-optics.

In contrast to bulk micromachining, surface micromachined structures are made entirely from thin films deposited on the surface of a wafer. Alternating layers of *structural* and *sacrificial* layers are successively grown and patterned on the substrate. Sacrificial etching, the key technology for surface micromachining, selectively removes sacrificial layers from underneath the structural layers, creating free-standing thin-film mechanical structures. Sacrificial etching was initially used to produce mechanically resonant field effect transistors in 1967.[3] Polysilicon thin films and silicon dioxide sacrificial layers have become the most popular surface micromachining materials because of their excellent mechanical properties and the high selectivity of sacrificial etching.[4] Other material combinations have also been demonstrated. For example, Texas Instruments uses aluminum structural layers and organic sacrificial layers for their digital micromirror device;[5] nearly a million micromirrors have been integrated on silicon chips with a complementary metal-oxide-semiconductor (CMOS) transistor driving circuit for projection display application.

Micromachined free-space micro-optical bench

MEMS technology has made it possible, for the first time, to integrate an entire optical table onto a single silicon chip. Optical elements such as lenses, mirrors, and gratings are batch fabricated along with the XYZ stages and the microactuators. A free-space micro-optical bench (FS-MOB) is illustrated in Figure 1. Here, several XYZ stages are used to align the microlenses and a tunable optical delay line to form a femtosecond optical autocorrelator. Similarly, many other optical functions can be implemented on an FS-MOB. FS-MOBs offer many advantages over conventional optical systems.

Low-cost batch processing

Unlike conventional optical systems with custom design and expensive assembly, the batch-fabrication process, similar to those used in the integrated circuit industry, can produce FS-MOB wafers with high throughput. This significantly reduces the cost per wafer or per FS-MOB chip.

Compact and lightweight

Many optical systems are limited by the sizes of the micropositioning stages and optomechanical structures. MEMS micropositioners and actuators can greatly reduce the size and weight of optical systems.

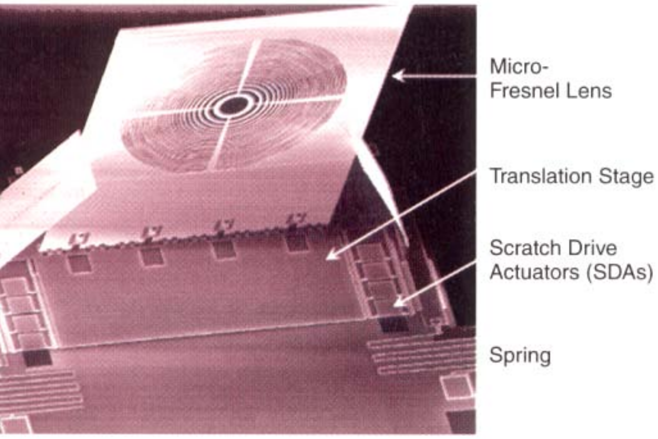

Figure 3. SEM of a micro-Fresnel lens with a translation stage. The translation stage is driven by the scratch drive actuator, which has a step size of 30 nm.

Standard process for different optical systems

Instead of developing a new process for each optical system, different optical functions can be realized by simply rearranging and resizing the basic building blocks of an FS-MOB. This enables fast prototyping of new optical systems and shortens the product development cycle.

Optical "pre-alignment"

Since FS-MOB uses photolithographic processes to make micro-optical elements and optomechanical structures at the same time, optical elements can be pre-aligned during layout of the photomasks. Optical pre-alignments establish the "interconnections" among the optical elements. This is similar to integrated circuits, where the interconnections between transistors are fabricated at the same time as the transistors. The mechanical clearance between the movable structures and the lithographic tolerance limits the accuracy of the alignment to a couple of micrometers.

On-chip microactuators

Perhaps the most striking difference between FS-MOB and conventional optical systems is that micromachined microactuators can be monolithically integrated with the optomechanical structures and micro-optical elements. These microactuators can perform fine optical alignment (with accuracy better than 0.1 μm), optical switching, scanning, or focusing and tracking in a dynamic environment.

Single-chip optical system

With MEMS ability to cascade multiple optical elements on the same substrate and to simultaneously fabricate micro-optics, optomechanical structures, and microactuators by the batch process, it is not hard to imagine that the entire optical system can be monolithically integrated on a silicon chip.

One of the most important building blocks of FS-MOB is the out-of-plane micro-optical elements[6] shown in Figure 1. Their optical axes are parallel to the substrate so that the optical elements can be cascaded, similar to the bulk optical systems built on optical tables. Conventional micro-optics fabrication techniques can only produce in-plane microlenses, that is, microlenses lying on the surface of the substrate. In MEMS FS-MOB, the surface-micromachined microhinges[7] can "flip up" the microlenses after they are fabricated. Figure 2 shows the fabrication process of an out-of-plane refractive microlens. First a hinged optomechanical frame is made using surface-micromachining. Then, the spherical microlens on the frame is formed by photolithography and the reflow process, a technique commonly used by the micro-optics community to make refractive lenses. (Or alternatively, grey-tone lithography can produce even more versatile microlens profiles.) After release etch, the optomechanical frame is free to rotate around the microhinges. The microlens is assembled in the upright position. Since the same surface micromachining process produces both the hinged optomechanical frames and the microactuators, the microactuators can be used to perform the assembly process.

The out-of-plane micro-optical elements can also be integrated with actuated translation or rotation stages for optical alignment or tuning of an optical circuit. Instead of anchoring the optomechanical plates to the substrate, it is attached to another suspended polysilicon plate, which is free to move in the direction determined by the confinement structures. Figure 3 shows an SEM of a micro-Fresnel lens integrated on a translation stage. The translation stage is driven by eight parallel actuators, called scratch drive actuators (SDA),[8] and balanced by a restoring spring. The SDA is basically a stepper motor with an extremely fine step size. It consists of a polysilicon plate with a vertical bushing. Upon application of an electrical pulse, the electrostatic force will deform the polysilicon plate. The downward motion pushes the front bushing forward by a small step. Upon release of the bias, the friction at the front bushing, which is larger than that at the backside of the plate, pulls the entire

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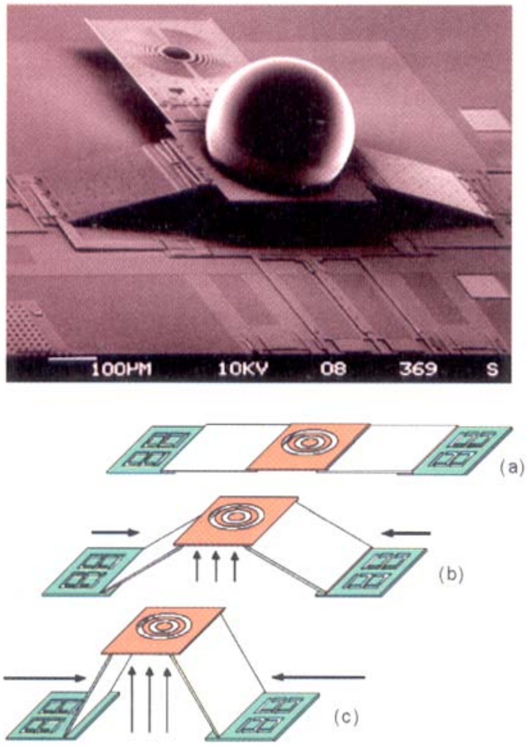

Figure 4. (top) SEM of a micro XYZ micropositioner with 3 degrees of freedom. The travel distance is greater than 120 μm for all three directions, and the step size of the actuator is 30 nm. (bottom) Schematic illustrating the self-assembly process of the micro-elevator.

SDA forward. The average step size is extremely fine, 20~30 nm, which is ideal for positioning optical elements requiring sub-0.1 μm accuracy.

Micro XYZ stages

XYZ micropositioning stages are widely used for alignment in optical systems built on optical tables. Building XYZ stages on a silicon wafer is challenging. Most surface-micromachined actuators move in the plane of the substrate (X and Y directions). The first challenge is how to achieve large displacement in the out-of-plane (Z) direction. The second challenge is how to combine the three-axis motions in a single device with independent control in each direction. Bulk XYZ micropositioners are made by vertically stacking three individual linear translation stages. However, in surface micromachining, there are only a finite number of structural layers [*e.g.*, there are only two polysilicon layers in the multi-user MEMS processes (MUMPs) offered by MCNC at North Carolina]. Each translation stage requires at least one to two structural layers. The third challenge is how to achieve large displacement and sub-micrometer resolution in all three directions. Most optical applications require a travel distance on the order of 100 μm and a resolution better than 1 μm. Aligning single-mode optical fibers or waveguides requires a resolution of 0.1 μm.

Recently, a novel micro XYZ stage using the surface micromachining technology was demonstrated.[9] The stage has three independent degrees of freedom and can move external micro-optical elements as well as integrated microlenses. Figure 4 is an SEM of the XYZ stage carrying a 300-μm diameter ball lens. The main body of the stage consists of a novel "micro-elevator" that can rise above the substrate by hundreds of micrometers. The micro-elevator is powered by in-plane microactuators only. It uses five hinged polysilicon plates (one center plate, two side-support plates, and two actuator plates) to convert in-plane motion to vertical displacement. By properly designing the polarities of the microhinges, the center plate will buckle up and rise above the silicon surface when the two actuator plates are pushed toward each other (see Fig. 4). We call this structure micro-elevator by self-assembly (MESA). Due to its motion amplification, a very large vertical displacement (250 μm) is achieved when the actuators move only 110 μm. The micro-elevator is then combined with an in-plane XY stage to form a fully integrated micro-XYZ stage. The MESA structure can translate laterally in X direction without changing the height if the moving direction of one actuator is reversed. This is a key factor for seamless integration of the Z with the X stage. Then the XZ stage is combined with the Y lateral translation stage through a "sliding joint" so that independent X and Y motion can be achieved. The SDAs described earlier have been used for all three stages to achieve large displacement (>120 μm in all three axes) and fine resolution (30 nm).

How the physical laws scale with size plays an important role in the successful operation of the micro-XYZ stage. The weight or gravitational force is proportional to the volume, and scales as $(\text{length})^{-3}$. When the structures shrink down to microscale, the gravitational and inertial forces become negligible compared with the frictional or actuator force. Therefore, the micro-XYZ stage can hold the microlens in place once the optical alignment is finished and the electrical bias is removed, even though the microlens in Figure 4 is about 100 times heavier than the stage itself.

MEMS fiber optic switch

Another application that MEMS technology can significantly impact is optical switches. Optomechanical switches offer many advantages over electro-optic or waveguide switches, including much lower optical insertion loss and crosstalk. Furthermore, optomechanical swithches are insensitive to the wavelength, bit rate, or polarization of the data, which makes them attractive for applications such as network restoration or reprovisioning. Conventional optomechanical switches are, however, bulky, expensive, and unreliable. MEMS technology, therefore, provides a potential solution for reducing the size, weight, and cost of these switches.[2] Under Defense Advance Research Project Agency (DARPA) support, UCLA has been investigating manufacturable, low-cost fiber optic switches using MEMS technology.[4] The schematic structure and an SEM of the switch, shown in Figure 5, consist of a moveable micromirror, four fiber guides, a mechanical restoring spring, and microacuators. Depending on the mirror position, light emitted from the input fiber is either transmitted to the opposite fiber or reflected to the orthogonal fiber. The SDA and a restoring spring are used to move the micromirror. The restoring spring allows the switch to be used as a "bypass" switch for the fiber distribution data interface (FDDI) ring networks. During power failure, the spring always pulls the mirror back to the "bypass" state to maintain the continuity of the fiber ring network.

The MEMS fiber optic switches have inherently low optical insertion loss and crosstalk. The optical insertion losses include the coupling loss of fiber collimators at input and output fibers, and reflection loss at the MEMS micromirrors. Typical fiber collimators have losses of 0.2 to 0.5 dB. Therefore, the total insertion loss of a MEMS fiber optic switch could be made below 1 dB. Larger optical switches could encounter higher losses due to longer optical paths, but in general the losses are still much lower compared with other types of switches. Furthermore, since the light is usually completely blocked and reflected to the output channel, the isolation and crosstalk are very small (typically below the measurement limit of –60 dB). MEMS switches are also much faster than conventional optomechanical switches. As the size of the switch scales down to micro scale, the mass becomes miniscule and its resonant frequency becomes very high. Typical MEMS switching time is below a millisecond.[10] For special devices with very small displacement, switching times as short as 100 ns have been demonstrated.[11]

One unique advantage of the MEMS optical switch is its ability to scale up to large switch arrays. With the miniaturization of the MEMS, a large number of the optical switches can be monolithically integrated on the silicon substrate. This technology is ideally suited for optical crossconnect applications. Optical crossconnects with large port counts are quickly becoming the much-needed void of optical switches with a large number of input/output fibers and a very low insertion loss and crosstalk. Recently, an 8 × 8 MEMS optical crossconnect was demonstrated.[12] Continual development in optical MEMS technology could lead to even larger switches in the near future.

The ability to integrate optical and actuated mechanical components on the same chip using MEMS technology opens up many new opportunities. Optical switches with small insertion loss and low crosstalk, and XYZ stages with nanometer accuracy are just two examples. Eventually, an entire optical system can be monolithically integrated on a single chip. A new family of optical and optoelectronic devices can be built at low cost by batch processing techniques. These devices are smaller, lighter, faster, more rugged, and more functional than their bulk optomechanical counterparts. This new technology will have a large impact on optical switching, telecommunication, display, printing, scanning, and optical data storage applications in the near future.

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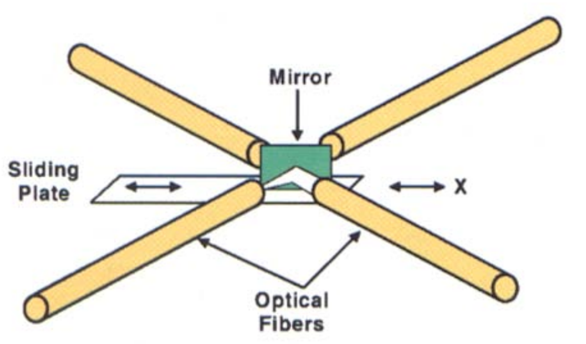

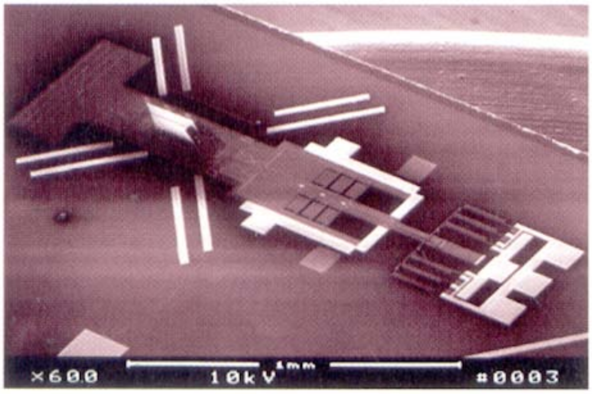

Figure 5. (top) Schematic and (bottom) SEM of the 2 × 2 MEMS fiber optic switch.

Acknowledgments

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