MEMS Optical Switches

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ABSTRACT

Leveraging MEMS's inherent advantages such as batch fabrication technique, small size, integratability, and scalability, MEMS is positioned to become the dominant technology in optical crossconnect switches. MEMS optical switches with complex movable 3D mechanical structures, micro-actuators, and micro-optics can be monolithically integrated on the same substrate by using the matured fabrication process of the integrated circuit industry. In this article we report various popular actuating mechanisms and switch architectures of MEMS optical switches. The basics of surface and bulk micromachining techniques used to fabricate MEMS devices will be reviewed. Examples of 2D and 3D approaches to MEMS optical switches will be described. The pros and cons of the two approaches will be analyzed. In the short term, MEMS-based optical switches seem to have captivated the attention of both the industry and academia. However, there are challenges that threaten the long-term survival of this technology. The problems that remain to be fully addressed will be discussed.

INTRODUCTION

One of the most promising applications of microelectromechanical systems (MEMS) technology is in optical communication in general and optical crossconnect (OXC) switches in particular. The OXC switches in today's network rely on electronic cores. As port count and data rates increase, it becomes increasingly difficult for the electronic switch fabrics to meet future demands. It is widely acknowledged that electronic switch fabrics are the bottleneck in tomorrow's communication networks. This bottleneck has stimulated intensive research in developing new all-optical switching technologies to replace the electronic cores. All-optical networks offer many advantages compared to conventional optical-to-electronic and electronic-to-optical networks, including cost-effectiveness, immunity from electromagnetic interference, bit rate/protocol transparency, and ability to implement wavelength-division multiplexing (WDM) with relative ease. Therefore, it is desirable to manipulate the data network at the optical level with optical switches. The optic switches are used to reconfigure/restore the network, increase its reliability, and/or act as the optical add/drop multiplexer (OADM). There are, indeed, many technologies competing to replace the current electronic switch fabrics. A successful optical switching technology will have to demonstrate superiority in the areas of scalability, insertion loss, polarization-dependent loss (PDL), wavelength dependency, small size, low cost, crosstalk, switching speed, manufacturability, serviceability, and long-term reliability. Conventional mechanical switches, which are based on macroscopic bulk optics, utilize the advantages of free-space optics; however, they suffer from large size, large mass, and slow switching time. On the other hand, guided-wave solid state switches have yet to show great potential because their high losses and high crosstalk limit their scalability. The recent development of free-space optical MEMS technology has shown superior performance for this application. MEMS optical switches not only retained their conventional counterparts' advantages of free-space optics such as low losses and low crosstalk, but also included additional ones such as small size, small mass, and submillisecond switching times. Furthermore, MEMS fabrication techniques allow integration of micro-optics, micro-actuators, complex micromechanical structures, and possibly microelectronics on the same substrate to realize integrated microsystems.

MICROMACHINING TECHNIQUES

MEMS fabrication techniques utilize the mature fabrication technology of the Integrated Circuit (IC) industry. The fact that silicon is the primary substrate material used in the IC circuitry and that it also exhibits excellent mechanical properties [1] make it the most popular micromachining material. The micro-mechanical structures used in MEMS optical switching can be fabricated using two popular micromachining technologies, bulk micromachining, and surface micromachining.

BULK MICROMACHINING

This is the most mature and simple micromachining technology. Bulk micromachining is sometimes called the etching/subtraction process. It involves the removal of silicon from the

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bulk silicon substrate by etchants. There are two types of chemical etchants, anisotropic and isotropic. Anisotropic etchants etch different silicon orientation planes at different rates. Figure 1a shows the silicon planes exposed by using anisotropic etchants. Figure 1b shows a 3D mechanical structure that was fabricated using anisotropic etching.

Isotropic etchants, on the other hand, etch the silicon evenly in all directions. Figure 1c shows the effect of isotropic etches on silicon substrate. Note that the mechanical structure that can be created by bulk micromachining is not very complex.

SURFACE MICROMACHINING

Surface micromachining is a more advanced fabrication technique. Complex 3D mechanical structures can be created using alternate layers of sacrificial and structural materials. Sacrificial layers act as spacers between structural layers. Free-standing 3D mechanical structures will be formed when the sacrificial layers are etched away during final release. In surface micromachining, thin-film materials are selectively added to or removed from the wafer. Thin-film material deposited where a free-standing mechanical structure is needed is called a sacrificial layer. The material that is left after etching of the underlying sacrificial layer is called the structural material. In surface micromachining, a combination of dry and wet etching, and thin-film deposition are essential processes to realize micromechanical structures on silicon. A sacrificial layer, such as silicon dioxide, are deposited or grown underneath a patterned material for later removal. The removal process is usually done by chemical etching. After the removal of the sacrificial layer, the patterned material is left as thin-film free-standing mechanical structures as they are suspended over the substrate by the thickness of the etched sacrificial layer. Figure 2 shows the surface micromachining process of creating a free-standing mechanical structure. An insulation layer has been deposited on the silicon substrate, followed by deposition of SiO_2 as the sacrificial layer. The structural layer is then deposited on the SiO_2. Openings are etched in the structural layer to expose the sacrificial layer. The underlying sacrificial layer is etched away to release the free-standing structural layer.

SWITCH ARCHITECTURES

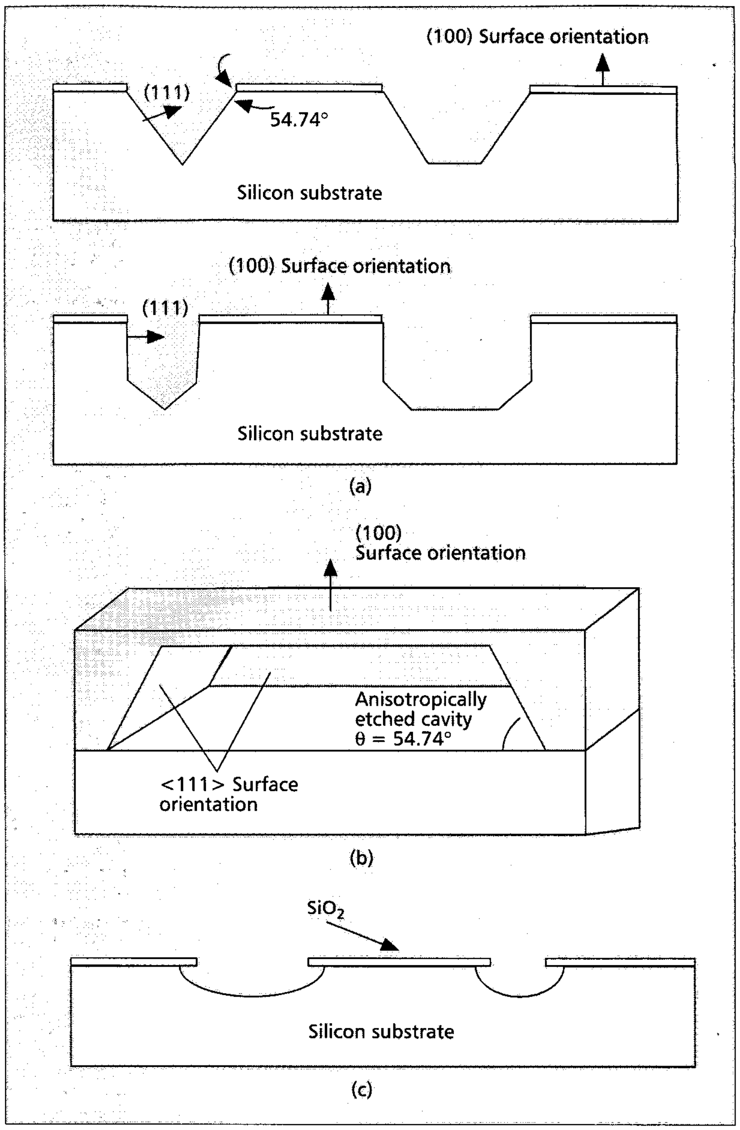
There are currently two popular approaches to implement MEMS optical switches:

- 2D MEMS switches
- 3D MEMS switches

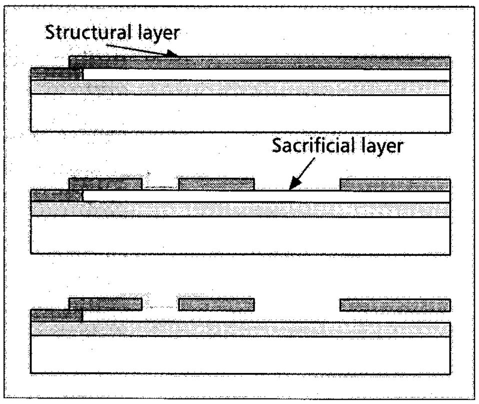
These two technologies have striking differences in terms of how they are controlled and their ability to redirect light beams. However, both of them have shown promise in finding their niches in telecommunication networks.

2D MEMS SWITCHES

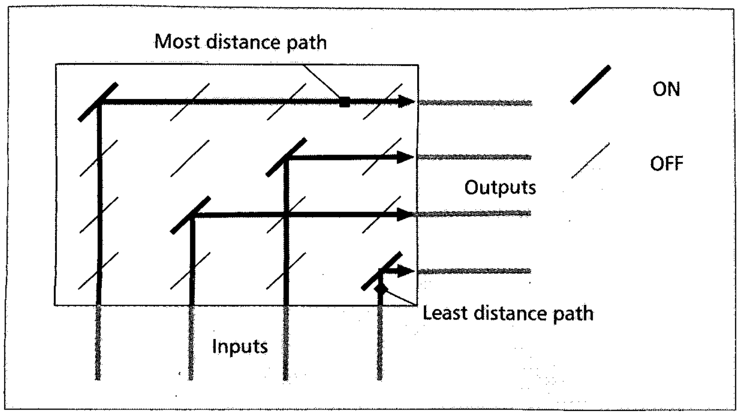
In this architecture mirrors are arranged in a crossbar configuration as shown in Fig. 3. Each mirror has only two positions and is placed at the intersections of light paths between the input



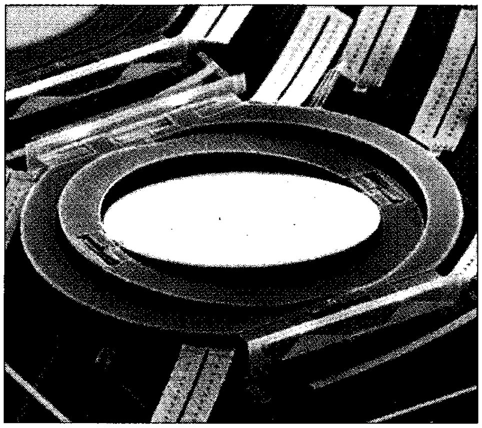
■ **Figure 1.** *a) Anisotropic wet etching of (100) and (110) silicon substrate; b) deep cavity form in silicon by anisotropic etchants; c) isotropic etching of silicon.*



■ **Figure 2.** *Surface micromachining process where the sacrificial layer is first deposited or grown for later removal. In the process, free-standing mechanical structures are released.*



■ **Figure 3.** *A 2D crossbar switching architecture.*



■ **Figure 4.** *A closeup view of a WaveStar™ MEMS mirror [2].*

and output ports. They can be in either the ON position to reflect light or the OFF position to let light pass uninterrupted. The binary nature of the mirror positions greatly simplifies the control scheme. Typically, the control circuitry consists of simple transistor-transistor-logic (TTL) gates and appropriate amplifiers to provide adequate voltage levels to actuate mirrors.

For an $N \times N$-port switch, a total of N^2 mirrors is required to implement a strictly nonblocking optical switching fabric. For example, a 16 × 16-port switch will require 256 mirrors. An alternative approach to increasing port count is to interconnect smaller 2D MEMS switch submodules to form multistage network architecture such as the well-known Clos network. However, this cascaded architecture typically requires up to thousands of complex interconnects between switch submodules, thus decreasing serviceability of the overall switching system. In addition, the free-space beam propagation distances among port-to-port switching are not constant; therefore, insertion loss due to Guassian beam propagation is not uniform for all ports. The minimum and maximum insertion losses of OMM's 2D 16 × 16 switching subsystem has a difference of greater than 5 dB. 2D optical switches find applications in areas of communication networks, which requires smaller port sizes.

3D MEMS SWITCHES

A 3D or analog MEMS switch has mirrors that can rotate about two axes. Light can be redirected precisely in space to multiple angles — at least as many as the number of inputs. This approach results in only N or $2N$ mirrors. Currently, a majority of commercial 3D MEMS switch designs use two sets of N (total of $2N$) mirrors to minimize insertion loss. Alternatively, if only N mirrors were used, port count would be limited by insertion loss that results from finite acceptance angle of fibers/lens. Another advantage is that differences in free-space propagation distances among ports-to-ports switching are much less dependent on the scaling of the port-count. This architecture can be scaled to thousands by thousands of ports with high uniformity in losses. Inevitably, much more complex switch design and continuous analog control are needed to improve stability and repeatability of the mirror angles. Lucent Technologies announced a 3D optical crossconnect using MEMS mirror array called WaveStar™ LambdaRouter [2]. The mirror can rotate on two axes and is continuously controllable to tilt greater than ±6°. Figure 4 shows a closeup view of the WaveStar MEMS mirror.

In the first quarter of 2001, Agere Systems, the former Microelectronics Group of Lucent Technologies, announced a fully integrated, 3D 64 × 64 MEMS optical switch component that will be marketed to makers of optical networking systems. The 5200 series MEMS switch module is based on the scalable 3D switching architecture developed at Lucent Technologies. Amazingly, the switching module has a maximum insertion loss of 6 dB and a switching time of less than 10 ms. Another notable development in 3D MEMS optical switch is by Nortel Networks. Nortel made headlines at Optical Fiber Conference (OFC) 2000 by showing the first ever all-optical switch, called the X-1000, to beat the 1000-port barrier. Following the hype created at OFC 2000, Nortel has recently admitted that only a small portion of the X-1000 actually worked. Nortel's 3D switching architecture is illustrated in Fig. 5.

Nortel's 3D switching architecture utilizes two sets of N mirrors for a total of $2N$ mirrors. The first plane of N mirrors redirect light from N input fibers to the second plane of N mirrors. All the mirrors on the second plane are addressable by each mirror on the first plane making nonblocking connections. In turn, mirrors on the second plane can each be actively and precisely controlled to redirect light into desired output fibers with minimum insertion loss.

ACTUATING MECHANISMS

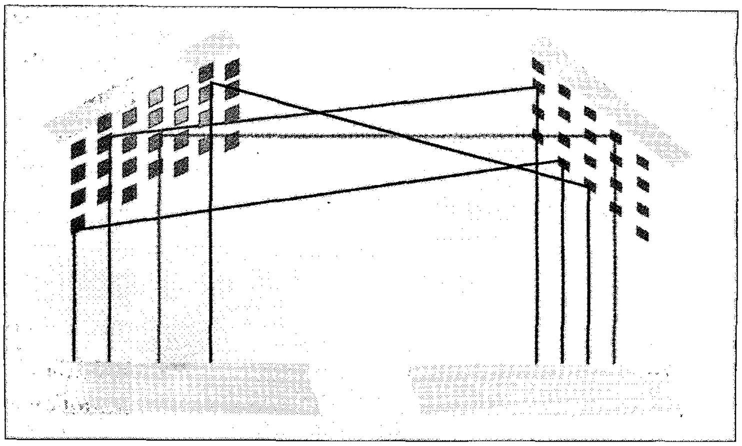
MEMS tilting mirrors alter the free-space propagation of light beams by moving into their propagation paths, thus achieving their switching functionality. In order for MEMS to be a viable optical switching technology, the actuating mechanisms used to move these mirrors must be small, easy to fabricate, accurate, predictable, reliable, and consume low power. This section briefly describes three actuating mechanisms that are being researched extensively in the university laboratories as well as the industry.

ELECTROSTATIC

Electrostatic forces involve the attraction forces of two oppositely charged plates. The advantages of electrostatic actuation are that it has very well researched and understood behavior. Furthermore, it has very good repeatability, a property very important in optical switching. The disadvantages include nonlinearity in force vs. voltage relationship, and requirement of high driving voltages to compensate for the low force potential.

The design usually involves mirrors being held in parallel plane (OFF) to the underlying electrodes. When an electrode is charged at a different voltage level than that of its corresponding mirror, the mirror will be tilted down to its ON position and thereby reflect a light beam to a different output fiber. Toshiyoshi and Fujita of the University of Tokyo demonstrated a 2 × 2 switching matrix using electrostatic actuation. An optical switching matrix with large isolation of 60 dB and small crosstalk of –60 dB and insertion loss of 7.66 dB are achieved using a bulk micromachined torsion mirror [3]. Figure 6 shows a 2 × 2 switching matrix with collimated light beams from input collimated beam fibers (CBFs) being reflected off torsion mirrors, fabricated at 45° to light beams, into receiving CBFs.

One of the leading MEMS optical switching companies, OMM, has already started shipping MEMS switching subsystems, based on electrostatic actuation, in production quantities since the spring of 2000. 2D switching subsystems of sizes 4 × 4, 8 × 8, and 16 × 16 are hermetically sealed and passed Telcordia Technologies' environmental and reliability requirements for carrier-class equipment. Passing of the stringent Telcordia tests, which include mechanical reliability and endurance, will help to facilitate widespread acceptance of MEMS-based switching subsystems in telecommunication networks. These switches have been used to route live data traffic in an unmanned central office in Oakland, California, with great success. OMM cites insertion loss of more than 6 dB, crosstalk of –50 dB, and switching time of 13 ms for a 16 × 16 subsystem.

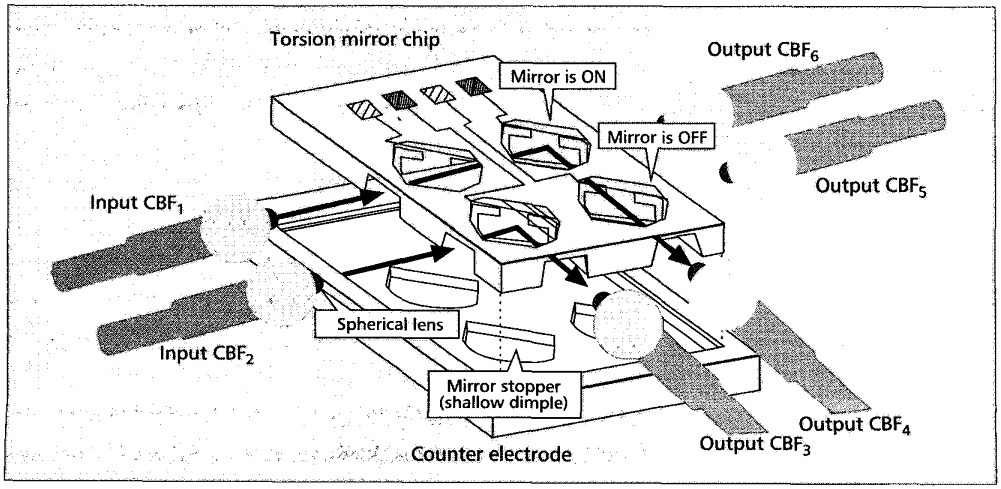


■ Figure 5. *A schematic illustration of Nortel's 3D switching architecture.*

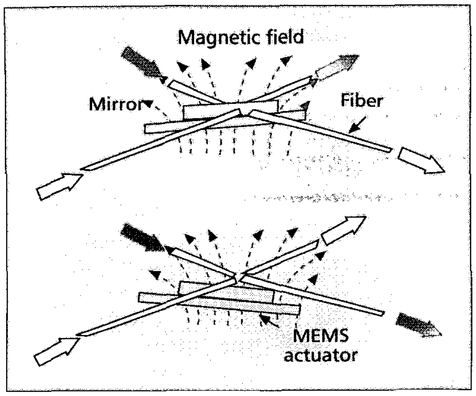
ELECTROMAGNETIC

Electromagnetic actuation involves attraction between electromagnets with different polarity. The advantages of electromagnetic actuation are that it requires low driving voltages because it can generate large forces with high linearity. Disadvantages such as shielding from other magnetic devices to prevent crosstalk is difficult, and it has yet to prove reliable. The California Institute of Technology has developed a magnetic 2 × 2 MEMS fiber optical bypass switch [4]. The operation principle of the magnetic MEMS switch is illustrated in Fig. 7. The thin double-sided bulk-micromachined mirror moves up or down in response to changing magnetic field. When the mirror moves up, it blocks the optical path to opposing optical fibers. In this case, light signal is reflected off the mirror into neighboring optical fibers. When the mirror moves down, it moves below the level of the optical fibers, and light signal is transmitted to opposing optical fibers. Electromagnetic actuation can achieve this displacement with less than 100 mW.

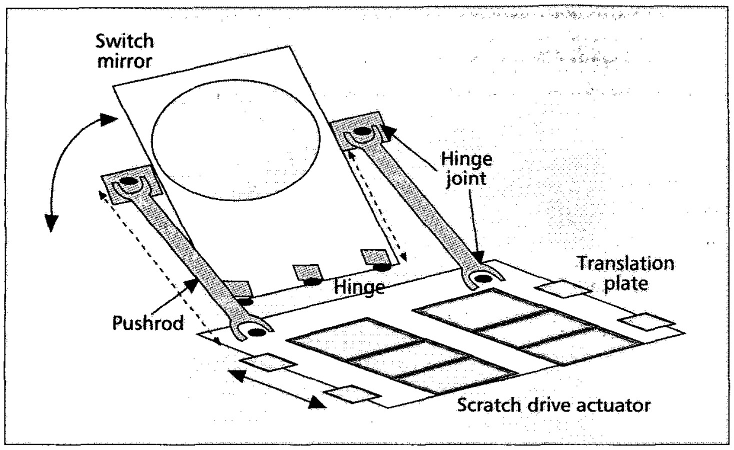
Integrated Micromachines Inc. (IMMI), based in Monrovia, California, has developed a 3D MEMS switching subsystem that has much lower loss than its competitors. It claims an



■ Figure 6. *An overall 2 × 2 optical switching matrix design [3].*



■ **Figure 7.** *A schematic illustration of operation principle of the 2 × 2 bypass fibre optic switch [4].*



■ **Figure 8.** *A schematic design of a free-rotating fiber optic switch [5].*

insertion loss of 3 dB regardless of switch size. By using electromagnetic actuation instead of the weaker electrostatic actuation, IMMI claims that the driving voltage does not exceed a maximum of 10 V. Low power requirement is a critical criterion especially when IMMI is looking to develop so-called 1000 × 1000-port monster switching subsystems. Low insertion loss and low power consumption bring benefits on both the system and economic levels. Now less optically efficient but more manageable fiber array connectors can be used, thereby reducing servicing time. In addition, MEMS/complementary metal oxide semiconductor (CMOS) integration, which eliminates tens of thousands of individual mirror control wires, is possible with lower voltage requirements.

SCRATCH DRIVE ACTUATORS

AT&T research labs have demonstrated an 8 × 8 free-space micromachined optical switch (FS-MOS) for the application of restoration and provisioning in core transport lightwave networks [5]. The mirror and the scratch drive actuators (SDAs) are monolithically integrated on the silicon substrate using surface micromachining techniques. The rotation of the mirror is achieved by connecting the pushrods with the mirror and the translation plate using micro-hinges [6]. The actuators used are an array of SDAs [7]. The translation movement of the translation plate by the SDAs is converted to a rotation movement of the mirror. Figure 8 shows the complete structural design of the FS-MOS. The length of the pushrod is 75 μm, and the distance between the hinges at the bottom of the mirror to hinge joint located on the mirror is 70 μm. This design allows the mirror to be rotated up to 45° when the translation plate is moved 2 μm, and 90° at a translation distance of 22 μm. The number of bias pulses applied to the SDAs determines the plate translation distance, and thus the rotation angle.

The optical switch has shown to have a switching time of 700 μs for rotating the mirror from an OFF position to the ON position. Losses measured range from a minimum of 3.1 dB to a maximum of 3.9 dB. In this design, SDAs have been shown to have very fast responses and extremely precise translation movement. With the presence of the pushrod and hinge joints, the mirror can be rotated to multiple angles precisely and reliably, two of the most important requirements of 3D MEMS switches. As discussed earlier, the current 3D MEMS switches require the mirrors to be rotated about two axes. Novel designs incorporating SDAs to provide precise positioning of mirrors about two axes of rotation have the potential to reduce needs for complex feedback control electronics.

CHALLENGES

In the short term, MEMS appears to be the forerunner that has the potential to dominate applications including OXCs, OADMs, and service restoration/protection switches. There remain important issues within MEMS technology that need to be addressed before widespread acceptance in the core transport network.

Reliability — Like any other commercially viable products, MEMS switches should function reliably in changing and often adverse environments. Will the behavior of MEMS switches that have been held in the ON position for a few months before switching to OFF during network restoration/provision be predictable? Or will stiction between materials restrict the movements of the switches? Will switch response times and structural integrity of the optical switches degrade after millions upon millions of switching cycles? Concerns regarding reliability of MEMS-based devices and repeatability in terms of performance need to be well studied in the context of entire optical systems.

Manufacturability — Characteristics of MEMS-based devices could fluctuate from one batch to the next. Repeatability of material properties and uniformity of processing techniques have to be improved to fully address these concerns. MEMS/CMOS fabrication processes have to be made compatible. The control electronics and wiring schemes can be fabricated in sync with MEMS components, thereby eliminating costly hybrid integrations. Researches into novel materials and fabricating processes must be ongoing. MEMS should be driven by technology as well as basic science.

Serviceability — Matrices of micro-mirrors are fabricated using batch fabrication technique.

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