An Introduction to MEMS Optical Switches

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I. GLOSSARY

actuator:	a device that causes movement of parts in a machine
actuating:	causing movement of parts in a machine
all-optical network:	an optical network environment that exploits multiple channel wavelengths for switching, routing or distribution, using light to the almost total exclusion of electronics (Bates, 2001, p. 273)
bar state:	the state in which, a light beam is allowed to pass straight through from one optical fiber to another
beam divergence:	the spreading of a light beam as it exits a small aperture
bulk micromachining:	micromachining that involves directly etching the silicon substrate
buried oxide:	the layer of oxide that is buried beneath a thin silicon top layer
collimator:	a device that makes divergent or convergent rays more nearly parallel
coupling:	the act of transferring energy from one optical component to another
coupling loss:	the loss that occurs when transferring energy from one optical component to another
crosstalk:	the undesired coupling of a signal from one channel to another
cross state:	the state in which, a light beam is deflected from one optical fiber into another perpendicular optical fiber
deep reactive ion etching (DRIE):	an etching process that allows for very high-aspect-ratio etching of silicon

electromagnetic actuation:	the movement of machine parts by electromagnetic forces
electrostatic actuation:	the movement of machine parts by electrostatic forces of attraction
electrostatic comb drive actuator:	an electrostatic actuator that uses a large number of interdigitated fingers
free-space microoptical bench (FS-MOB):	a scheme whereby micro-optical elements, micropositioners and microactuators are attached to on the same substrate, but the light beams travel in air
Fresnel reflection:	the reflection of part of the incident light at the sharp boundary between two media with different refractive indices (American National…, 2000)
fringe fields:	electromagnetic fields at the edges of conductors
hysteresis behavior:	the dependence on prior history of a difference in a state
insertion loss:	the total optical power loss caused by insertion of an optical component in an optical fiber system
integrated circuit (IC):	a semiconductor chip which contains dozens to millions of transistors
laser diode:	a semiconductor device that emits light when an electrical current is applied
mask:	a template containing the patterns of a layer
MEMS optical switch:	an optical switch implemented with MEMS technology
microelectromechanical systems (MEMS):	micron-size mechanical components such as levers, plates and hinges which are formed on a substrate (usually silicon) and actuated by electrical means
micromachining:	machining of structures at the microscale, often in silicon

micromirror:	a tiny mirror fabricated in silicon using MEMS technology
mode:	a pattern of electric and magnetic fields having a physical size (Crisp, 2001, p. 61)
mode coupling:	the transfer of energy from one mode of transmission to another
optical add/drop multiplexer:	an optical network component that lets specific channels of a multi-channel optical transmission system to be dropped and/or added without affecting the other signal channels that are to be transported through the network node (Bates, 2001, p.284)
optical cross connect (OXC):	a large optical switch capable of simultaneously switching many input optical signals to any output ports
optical-electronic-optical (O-E-O) switch:	a switch that first converts optical signals into electrical signals to perform the switching function, and then converts the electrical signal back into an optical signal for further transmission
optical fiber:	a cylindrical optical waveguide for transmitting light
optical switch:	a device that switches an optical signal from one optical fiber to another, without having to first convert the optical signal into an electrical signal
photodetector:	a device that detects light and generates an electrical signal
photoresist (resist):	a light-sensitive material that is used in the patterning process
polarization:	the direction of the electric field in electromagnetic waves
port count:	the number of input and output ports in an optical switch

rise time:	the time taken for the light intensity to increase from 10% to 90% of its final level
rotary electrostatic actuator:	an electrostatic actuator capable of causing rotation
shielding:	insulating from the effects of electrical or magnetic fields
silicon-on-insulator (SOI):	silicon wafer with a layer of buried oxide beneath a thin silicon surface layer
silicon substrate (bulk):	a thin slice (wafer) of silicon
silicon wafer:	see silicon substrate
single mode fiber:	an optical fiber with only one mode of transmission
synchronous optical network (SONET):	a standard for transmitting digital information over optical networks (Bates, 2001, p. 288)
surface micromachining:	micromachining that involves selectively etching the additional layers deposited on the silicon substrate
v-groove:	a V-shaped trench used to hold and align optical fibers

II. LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOLS

A	amplitude (in section on insertion loss)
A	plate area (in section on actuating mechanisms)
C	capacitance
ΔC	change in capacitance
ΔL	change in overlap length of fingers
ε_o	permittivity of free space
ε_r	relative permittivity of dielectric material
F	attractive force between plates
h	height of fingers
L	overlap length of fingers
λ	wavelength of light
n	number of fingers in lower comb (in section on actuating mechanisms)
n	refractive index (in section on insertion loss)
P	optical power delivered
P_{scat}	flux of light scattered away
P_{tot}	total reflected flux
σ	root mean square surface roughness
θ_i	angle of incidence
V	differential voltage
w	beam radius

W	energy stored by a parallel-plate capacitor
x	separation between plates (in actuating mechanisms)

ABBREVIATIONS

DRIE	deep reactive ion etching
IC	integrated circuit
Marxer et al. optical switch	two-dimensional 2x2 MEMS optical switch by Marxer et al.
MEMS	microelectromechanical systems
O-E-O	optical-electronic-optical
OXC	optical cross connect
SEM	scanning electron microscope
SOI	silicon-on-insulator
SONET	synchronous optical network
FS-MOB	free-space microoptical bench

III. INTRODUCTION

The purpose of my library research has been to study Microelectromechanical Systems (MEMS) optical switches, and to introduce this topic to newly graduated engineers who are unfamiliar with this area. Optical switches are components in a fiber-optic communications network that direct light beams from one optical fiber to another. Throughout this paper, the term “optical switch” shall refer only to switches that manipulate light beams directly. Switches that perform the switching function by converting the optical signal to an electrical signal are not included. MEMS technology (used to create microscale systems in silicon) is used to implement the optical switches that I have studied. I have focused on two-dimensional MEMS optical switches, and have chosen the two-dimensional 2x2 MEMS optical switch by Marxer et al. (1997, pp. 277-285) as an example for introducing some key features of two-dimensional MEMS optical switches.

IV. SOURCES

The major sources for my library research have been journal articles and conference proceedings. I have been using articles mainly from the *Journal of Microelectromechanical Systems* and *Laser Focus World*. I have also used conference papers written for the Optical Fiber Communication Conference and Exhibit. The IEEE Xplore website has also provided a number of useful on-line articles relevant to MEMS optical switches. For an understanding of fundamental concepts in MEMS and fiber-optics, I have relied on a number of introductory as well as advanced textbooks such as, *Introduction to Fiber Optics* by Crisp and *Micromachined Transducers Sourcebook* by Kovacs. I have also spoken with Cornell University Professors Ballantyne, Kan, Pollock and Lipson about various sections of this paper.

V. DISCUSSION

A. Background Information

(a) MEMS

According to Maluf (2000, pp. 3-4), MEMS is a very broad term that can refer to "techniques and processes to design and create miniature systems [at the microscale]." MEMS has been used to create miniaturized sensors, actuators and structures (often in silicon) for a variety of applications. A common example is the crash sensor used in automotive safety. The airbag deployment systems in automobiles have miniaturized sensors that monitor acceleration, and will produce a signal to activate the airbag deployment mechanism in the event of a crash. (Maluf, 2000, pp. 4-5) Despite having being discovered as early as the 1960's, MEMS is still finding its way into new applications, ranging from genetic and chemical analysis to telecommunications.

(b) Basic Micromachining Processes

Micromachining literally is the machining of structures at the microscale. MEMS products are usually made by micromachining silicon, which is the primary material used in the manufacture of integrated circuits (ICs). Hence, many of the processes in micromachining came from IC fabrication. (Maluf, 2000, p. 41) Micromachining is complex and involves several disciplines, including those of material science and chemistry. It is beyond the scope of this library research project to give a detailed treatment of micromachining. The intent in this section is to provide basic information, so that the process of fabricating MEMS optical switches may be understood.

The fabrication of MEMS products may involve several process steps. However, these steps can be grouped into three basic processes – deposition, patterning and etching. Figure 1 depicts these steps together with the cross-section of a silicon wafer. In deposition, layers of material are added on top of the silicon substrate (or bulk). The materials deposited include thin films of polysilicon, silicon dioxide, silicon nitrides and metals, such as aluminum, copper and tungsten. Photoresist (or resist) is a special type of material, similar to film used in photography. In the patterning step, the photoresist is exposed to light passing through a mask (a template containing the patterns of a layer) and is subsequently developed. Figure 2 illustrates the patterning process. A series of masks defines how to build the structures layer by layer. In etching, the undeveloped parts of the photoresist act as a protective layer, so that chemicals applied to the surface only remove material from the exposed regions. Hence, patterning and subsequently etching achieve selective removal of material. By repeating the three basic steps using different materials and chemicals, miniature structures are fashioned out of the silicon. (Maluf, 2000, pp. 42-69)

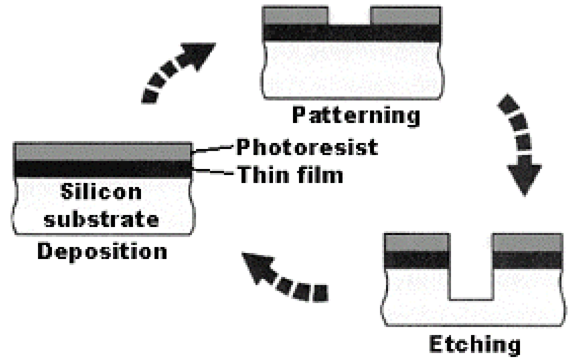


Figure 1: Three basic steps in micromachining (adapted from Maluf, 2000, p. 43)

Generally, two classes of micromachining are available for making MEMS products. In surface micromachining, layers of material are added to the surface of the silicon and are selectively etched to produce the structures. However, bulk micromachining involves directly etching the silicon bulk to form the structures. Thus, bulk micromachining does not add additional layers of material other than photoresist, which is required for patterning. (Neukermans and Ramaswami, 2001, p. 63)

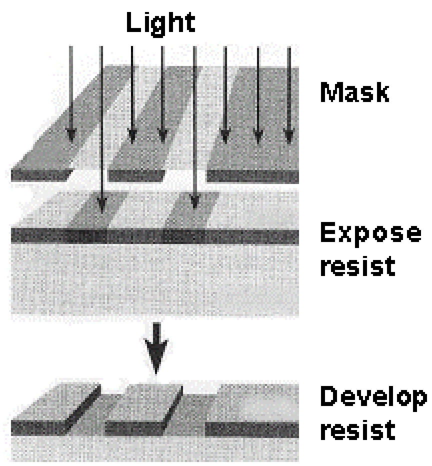


Figure 2: Patterning process (adapted from Maluf, 2000, p. 52)

(c) The need for optical switches

Optical switches have become important because of the telecommunications industry’s focus on all-optical networks. According to Bates (2001, p. 273), all-optical networks are “optical network environments that exploit multiple channel wavelengths for switching, routing or distribution, using light to the almost total exclusion of electronics.” The motivation for all-optical networks is evident from the bandwidth of an optical communication link. Today's optical fibers have an effective bandwidth of approximately 25THz (a unit of frequency equal to 10^{12} cycles per second). This amount of bandwidth can be regarded as infinite for today's applications. However, the optical-electronic-optical (O-E-O) switches that are currently being used to switch optical signals are limiting the use of the wide bandwidth of optical fibers. O-E-O switches first convert the input optical signal to an electronic signal using a high-speed photo-detector (a device that detects light and generates an electrical signal). Electronic circuits in the switch then perform the switching function, directing the electronic signal to the appropriate output port. Finally, a laser diode (a device that emits light when an electrical current is applied) converts the electronic signal back into an optical signal for further transmission on the optical fiber network. (Bates, 2001, p. 135) The O-E-O switches are unable to match the higher data rate of the optical fibers because of this conversion process, and they slow down the operation of the optical fiber communication link (Morris, 2001, p. 47).

As demand for bandwidth grows, due to increased Internet traffic and the advent of data- and video-centric networks, the need to eliminate this bottleneck at the switches becomes more critical. Optical switches that manipulate optical signals directly without converting the optical signal to an electronic signal have been developed to replace the O-E-O switches. One approach has been the use of MEMS technology to fabricate tiny mirrors that perform the switching function. These tiny mirrors (micromirrors) switch optical signals by reflecting the light beams, and switches using these tiny mirrors are known as MEMS optical switches.

B. Two-Dimensional and Three-Dimensional Architectures for MEMS Optical Switches

Generally, two approaches are taken in implementing MEMS optical switches. In the two-dimensional or digital approach, an array of micromirrors and the optical fibers are arranged so that the optical plane is parallel to the surface of the silicon substrate. The micromirrors can assume one of two states at any given time. (Husain, 2001, p. wx1-2) In the cross state, the micromirror moves into the path of the light beam and reflects the light beam, whereas in the bar state, it allows the light beam to pass straight through. Figure 3 is a diagram of a simplified two-dimensional 4x4 MEMS optical switch. The short diagonal lines represent micromirrors. The darkened mirrors are in the cross state while the grayed out micromirrors are in the bar state. Input light beams 1, 2, 3 and 4 are directed to output ports 3, 1, 4 and 2 respectively. With individual micromirrors in the cross state or bar state in the array, any input port can be connected to any output port. (Barthel and Chuh, 2001, p. 93)

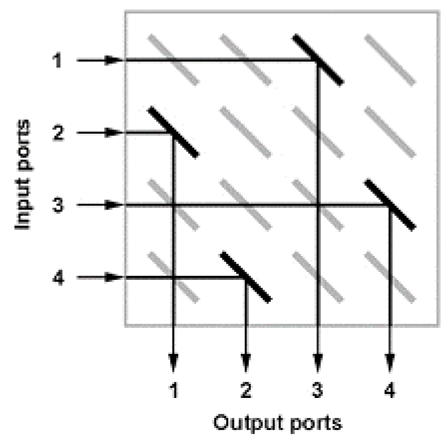


Figure 3: A two-dimensional 4x4 MEMS optical switch (adapted from Barthel and Chuh, 2001, p. 93)

In the three-dimensional or analog approach, the micromirrors are not limited to just two positions. They are able to vary their position over a continuous range of angles and in two directions, which allows a single micromirror to direct an input light beam to more than one possible output port (Hecht, 2001, p. 126). In contrast, in the two-dimensional approach, the micromirror in row one, column three for example, is able to direct only input light beam 1 to output port 3. According to Hecht (2001, pp. 125-126), a common three-dimensional micromirror is the two-axis tilting micromirror (see Figure 4). The circular micromirror "pivots on one axis between a pair of posts attached to a surrounding ring. The ring, in turn, pivots on a perpendicular axis on a pair of posts connected to a surrounding framework, which is fixed in place above the surface." Figure 5 depicts two arrays of these tilting micromirrors, used in an NxN MEMS optical switch. The light beams from an array of input ports fall onto the first array of tilting micromirrors, which reflects

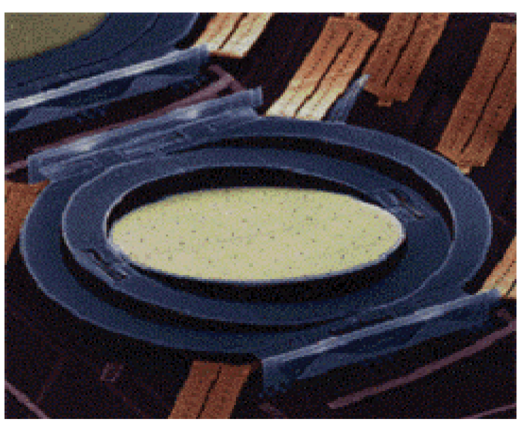


Figure 4: Two-axis tilting micromirror (Hecht, 2001, p. 125)

the light beams onto a second array. The second array then reflects the light beams into an array of output ports. Each micromirror on the first array is able to reach any of the micromirrors on the second array and vice-versa. (Hecht, 2001, p. 126)

For an NxN switch, the two-dimensional approach requires N^2 micromirrors, while the three-dimensional approach requires only 2N micromirrors. The three-dimensional approach scales much better with port count, as it is linear in N. Hence, as port count increases, the three-dimensional approach results in more compact designs than the two-dimensional approach. The two-dimensional approach also suffers from an increasing propagation distance for light as port counts grow. When the light beam exits the optical

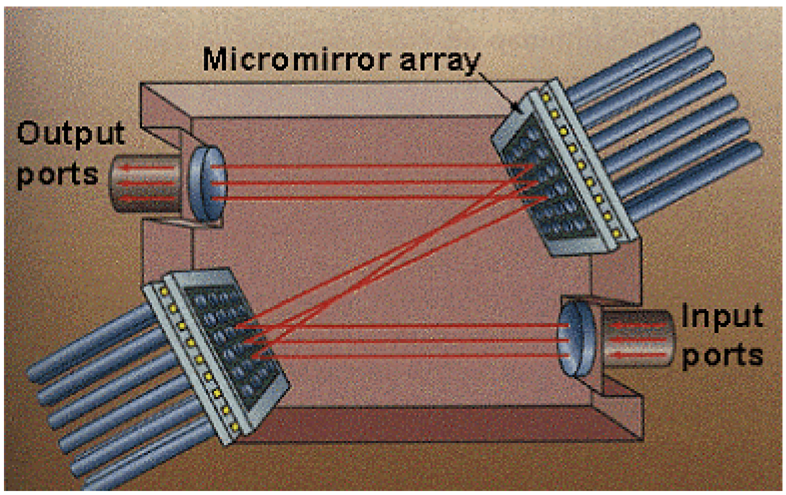


Figure 5: Arrays of tilting micromirrors in action
(adapted from Hecht, 2001, p. 126)

fiber, it begins to spread. The longer the distance traveled, the greater the beam's diameter becomes, resulting in the need for greater collimator (device that makes divergent or convergent rays more nearly parallel) performance. However, the two-dimensional approach has the advantage of being simpler and less sensitive to noise. The micromirrors in the three-dimensional approach have to be very precise. A small amount of noise present in the control circuit can cause an error in the tilt angle of the micromirror, leading to misdirection to the wrong port. (Husain, 2001, pp. wx1-2 – wx1-3)

C. The Two-Dimensional 2x2 MEMS Optical Switch by Marxer et al.

Appendix A shows the structure and operation of a simplified version of the two-dimensional 2x2 MEMS optical switch by Marxer et al. (1997, pp. 277-285). This optical switch (subsequently referred to specifically as the "Marxer et al. optical switch") uses a sliding vertical micromirror whose movement is controlled by an electrostatic comb drive actuator. The vertical micromirror is found at the intersection of two perpendicular alignment grooves. The optical fibers (only one is shown) lie in the alignment grooves. In (1), the optical switch is in the cross state and the vertical micromirror moves into the light path. The light beam from input 1 is reflected into output 2, and the light beam from input 2 is reflected to output 1. The optical switch is in the bar-state in (2). The vertical micromirror is retracted, and the light beams from inputs 1 and 2 are allowed to pass straight through into their respective outputs. (Maluf, 2000, pp. 187-190)

Appendix B explains the fabrication of the Marxer et al. optical switch. Bulk micro-machining with a silicon-on-insulator (SOI) wafer (silicon wafer with a layer of buried oxide beneath the silicon bulk) is used. Photoresist is applied, and patterning is performed as shown in (1). A single mask is used that contains the patterns for the micromirror, the optical fiber alignment grooves, the electrostatic comb drive actuator and the suspension springs. The left side of the cross-section corresponds to the electrostatic comb drive actuator and the right side to the optical fiber alignment groove. An etching process known as Deep Reactive Ion Etching (DRIE) is then used to obtain the deep trenches shown in (2). DRIE is capable of very high-aspect-ratio silicon etching of up to 200:1 aspect ratios. For a detailed discussion of DRIE, see pages 66 to 70 of Maluf's book. Etching stops when the buried oxide is exposed because the chemistry changes. In (3), hydrofluoric acid, which does not etch silicon, is applied to remove the buried oxide. By controlling the duration and rate of etching, the hydrofluoric acid does not etch away all the buried oxide in the SOI wafer. The movable structures are freed while the rest remain anchored. Finally, in (d), the optical fiber is placed into the alignment groove and the micromirror is coated with aluminum. (Maluf, 2000, pp. 66-70; Marxer et al., 1997, p. 279)

Two-dimensional 2x2 optical switches such as the Marxer et al. optical switch are the basic building blocks for two-dimensional optical switches of higher port count. Typically, these larger two-dimensional optical switches are formed by cascading a number of two-dimensional 2x2 optical switches in a matrix. Therefore, many of the features of two-dimensional MEMS optical switches are illustrated in the Marxer et al. optical switch presented above.

D. Micromirrors

Micromirrors are the centerpieces of MEMS optical switches. They are tiny mirrors fabricated in silicon using MEMS technology. The switching function is performed by changing the position of a micromirror to deflect an incoming light beam into the appropriate outgoing optical fiber. The three important properties of micromirrors are reflectivity, light transmission, and surface roughness. Coating its surface with metal can increase the reflectivity of a micromirror. Figure 6 shows a plot of micromirror reflectivity versus the thickness of metal coating for four different metals. The wavelength of light used was 1.3 μm and the measurements were taken for normal incidence. The micromirror reflectivity increases with increasing thickness of metal coating, and saturates at a maximum value. Coating the micromirror with aluminum appears to be the best option, giving the micromirror a maximum reflectivity of 97% at a thickness of 40 nm. A gold coating is also a good option, but the micromirror reflectivity only saturates to its maximum value at 60 nm. If the angle of incidence is non-normal, the reflectivity of the micromirror is dependent on the polarization of light. Polarization refers to the direction

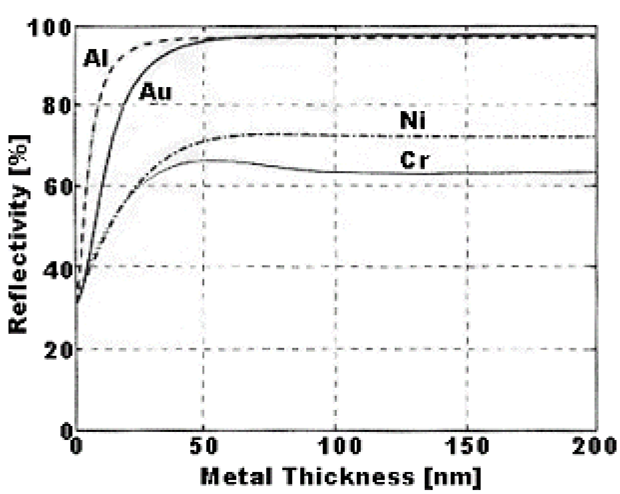


Figure 6: Micromirror reflectivity as a function of metal coating thickness
(adapted from Marxer et al., 1997, p. 278)

of the electric field in electromagnetic waves. The dependence varies for different metal coatings. For a 45^o angle of incidence, the aluminum-coated micromirror demonstrates a polarization dependence of only 1.1%, whereas for chrome and nickel, the polarization dependence is greater than 11%. (Marxer et al., 1997, pp. 277-278)

Ideally, the micromirror should only reflect light, but a small amount of light is also transmitted. The light transmission should be attenuated as far as possible so that no light passes through the micromirror. Otherwise, crosstalk into an undesired fiber would occur. It has been found that the light transmission is attenuated below 1 ppm for an aluminum coating thickness of 100 nm. Gold, chrome and nickel coatings all require a thickness in excess of 170 nm to achieve the same result. (Marxer et al., 1997, pp. 277-278)

If the surface of the micromirror is not smooth, light is scattered, resulting in light loss. The total amount of scattered light for a micromirror may be estimated using the equation

$$\frac{P_{scat}}{P_{tot}} = 1 - e^{-\left(\frac{4\pi\sigma\cos\theta_i}{\lambda}\right)^2}$$

where P_{scat} is the flux of light scattered away from the specular direction, P_{tot} is the total reflected flux, θ_i is the incidence angle, λ is the wavelength and σ is the root mean square surface roughness. This relationship is only valid for gently sloped surfaces with a Gaussian distribution of surface height (Marxer et al., 1997, p. 278). Zhu and Kahn (2001, pp. 185-186) provide a more advanced treatment of light loss due to micromirror surface roughness.

In the case of the Marxer et al. optical switch, additional properties of concern are micromirror verticality and thickness. The effect of a micromirror's verticality and nonzero thickness on coupling loss (the loss that occurs when energy is transferred from one optical fiber to another) has been studied. The mirror introduces an angular offset, as it is not exactly 90^o to the substrate. A traverse beam offset is also present due to the nonzero thickness. Figure 7 is a plot of coupling loss versus micromirror angle for four different micromirror thicknesses. The plot shows that the thickness of the micromirror should be kept below 3.5 μm for a 90° micromirror, and at most, 2 μm for an angle error of 0.7°, in

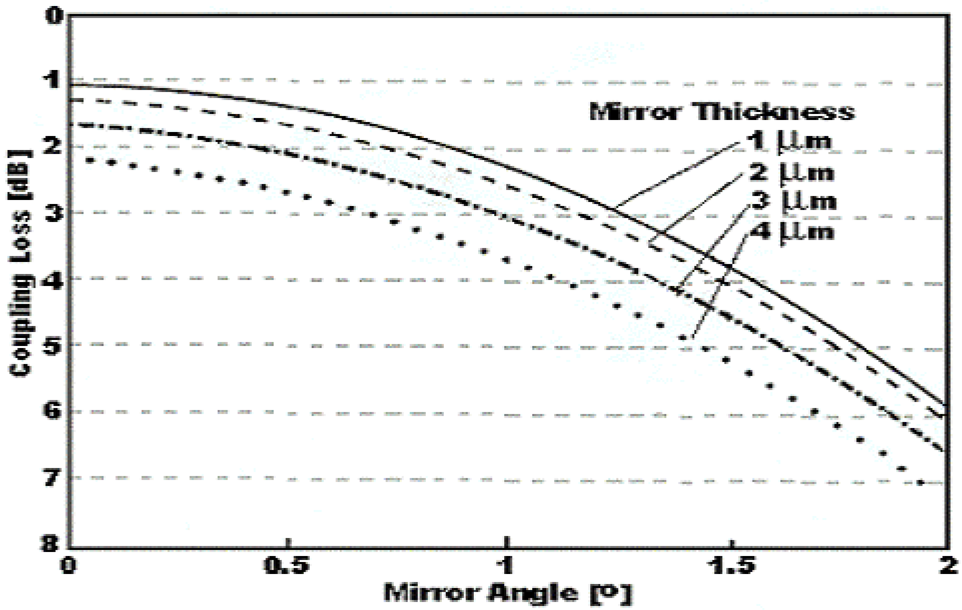


Figure 7: Coupling loss as a function of mirror angle for four different mirror thicknesses
(adapted from Marxer et al., 1997, p. 279)

order to achieve a coupling loss below 2dB. (Marxer et al., 1997, p. 279)

E. Actuating Mechanisms

(a) Electromagnetic Actuation

In electromagnetic actuation, electromagnetic forces are used to move the micromirror. An electromagnetic 2x2 MEMS optical switch has been successfully developed by Miller et al. (1997, pp. 89-92). The micromirror was fabricated on top of a silicon plate supported by cantilever beams. A copper coil is found on the bottom side of the silicon plate. The application of an electric current through the coil, in the presence of a magnetic field, exerts a force on the silicon plate. The force causes the cantilever supports to bend, thereby altering the position of the micromirror. Magnetic actuation can provide larger forces, but it suffers from high power consumption and problems with shielding neighboring objects from the magnetic fields (Kovacs, 1998, p. 649).

(b) Electrostatic Actuation

Electrostatic actuation relies on the attraction between two oppositely charged plates, and has the benefits of repeatability, no shielding requirements, and well-studied behavior (Husain, 2001, p. WX1-2). According to Kovacs (1998, p. 277), electrostatic actuators are also “very low power” and “simple to fabricate”. Electrostatic actuation is the method employed in the Marxer et al. optical switch, and will be discussed further.

Using a parallel-plate capacitor approximation, the force supplied by electrostatic actuation can be estimated to first order. The approximation holds only for simple geometries and very small angles (in the case of cantilevers). Neglecting fringe fields (fields at the edges of the plates), the energy stored by a parallel-plate capacitor, C, with plate area, A, and voltage, V, across its terminals is given by

$$W = -\frac{1}{2}CV^2 = -\frac{1}{2}\frac{\varepsilon_r \varepsilon_o A V^2}{x}$$

where x is the separation between the plates, ε_r, the relative permittivity of the dielectric material and ε_o, the permittivity of free space. Taking the derivative of W with respect to x yields the force between the plates:

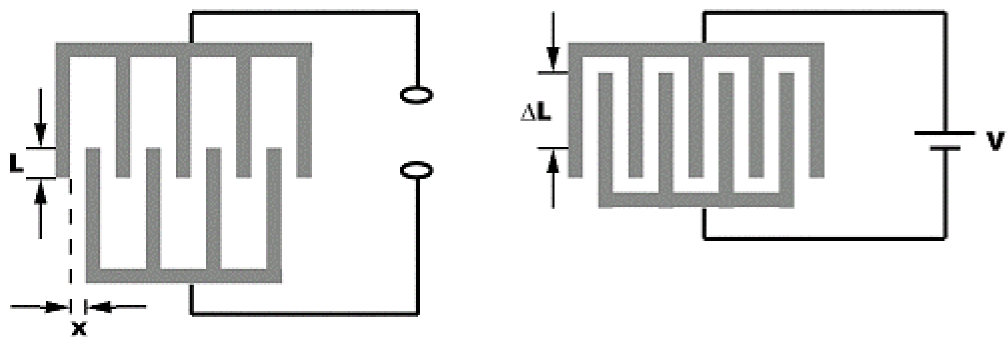
$$F = \frac{dW}{dx} = +\frac{1}{2}\frac{\varepsilon_r \varepsilon_o A V^2}{x^2}$$

This equation states that the force versus separation distance and force versus voltage relationships are non-linear (Kovacs, 1998, p. 278). Maluf (2000, p. 92) mentioned that the electrostatic force generated for a spacing of one μm, an applied voltage of 5V, and a “reasonable area” of 1,000 μm^2 is “merely” 0.11 μN. To obtain relatively large movements in the plane of the substrate, electrostatic comb drive actuators are used in the Marxer et al. optical switch. Electrostatic comb drive actuators are a type of electrostatic actuator that makes use of a large number of “interdigitated fingers” (Kovacs, 1998, pp. 282-283).

Figure 8(a) shows a simplified diagram of an electrostatic comb drive actuator in the unactuated state. The upper comb is held rigid while the lower comb is free to move. The capacitance of the electrostatic comb drive is approximately

$$C = \frac{2n\varepsilon_r\varepsilon_o Lh}{x}$$

where n is the number of fingers in the lower comb (n is four in Figure 1), x is the separation between the fingers, L is the overlap length of the fingers and h (not shown in the



(a) Unactuated (b) Actuated

Figure 8: Operation of electrostatic comb drive actuator (adapted from Böhringer, 1999)

figure) is the height of the fingers. When a differential voltage, V, is applied, the lower comb experiences an attractive force given by

$$F = \frac{1}{2}V^2\frac{dC}{dL}$$

in the vertical direction (with respect to the orientation in the figure). The lower comb does not move in the horizontal direction, as each finger on the lower comb experiences an equal force of attraction in both the left and right directions. The actuated state is shown in Figure 8(b). The change in capacitance, ΔC, when the lower comb moves by ΔL is given by

$$\Delta C = \frac{2n\varepsilon_r\varepsilon_o h\Delta L}{x}$$

Therefore,

$$F = \frac{n\varepsilon_r\varepsilon_o hV^2}{x}$$

and F is independent of ΔL, suggesting that F is due mainly to fringing fields as opposed to parallel-plate fields. (Böhringer, 1999) The above equation shows that the force supplied by an electrostatic comb drive increases linearly with the number of fingers on the lower comb. Hence, the electrostatic force generated can be made much larger than 0.11 μN by using a large number of fingers.

Other types of electrostatic actuators for moving micromirrors have been fabricated. Rotary electrostatic actuators have been demonstrated by Grade and Jerman (2001, pp. WX2-1-WX2-3). These rotary electrostatic actuators consist of special arrangements of modified comb drives, which enable rotation of the micromirror.

(C) Actuating Mechanism of the Marxer et al. Optical Switch

To minimize the switching time, the Marxer et al. optical switch actually uses two electrostatic comb drive actuators working in opposite directions. Figure 9 is a Scanning Electron Microscope (SEM) image, showing the inner and outer comb drives. When the outer comb drive is actuated, the micromirror is pulled out of the optical path, leaving the optical switch in the bar state. The cross state is achieved by actuating the inner comb drive, which pushes the micromirror into the optical path. In the unactuated state, the micromirror is "in a median position …[where] part of the light is transmitted and part of the light is reflected." (Marxer et al., 1997, p. 281) The unactuated state is an invalid state. Either the outer comb drive or the inner comb drive has to be actuated when there is an input optical signal, in order to ensure correct functioning of the optical switch.

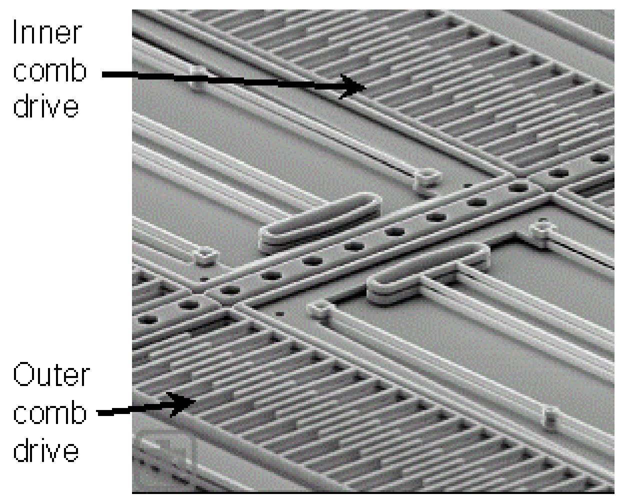


Figure 9: Inner and outer comb drives (adapted from Sandia National Laboratories, 2001)

The disadvantage of actuating the micromirror using this approach is that the optical switch consumes power in both the cross and bar state. However, the "combined action of the spring-restoring force and the electrostatic force" enables a faster switching time

(Marxer et al., 1997, p.281). The spring-restoring force comes from the suspension springs that hold the movable combs in place, when the micromirror is in the median position. If a single electrostatic comb drive were used, with the micromirror maintained in the retracted position, then the cross state would have to rely solely on electrostatic force to drive the micromirror. On the other hand, returning to the bar state would use only the force supplied by the suspension springs. Using the scheme with inner and outer comb drives, the total switching time measured is less than 0.2 ms and the 10% to 90% rise time is only 80 µs. (Marxer et al., 1997, p. 283)

The operation voltage is kept relatively small by the use of an outer and inner electrostatic comb drive (Marxer et al., 1997, p. 281). With two electrostatic comb drives, the work is shared between the two, resulting in a lower actuation voltage for each. Figure 10 illustrates the hysteresis behavior (difference in response of electrostatic comb drive actuator caused by prior state) of the electrostatic comb drive actuator. The transmitted power received by the output optical fiber is plotted as a function of applied voltage to the outer comb drive. The optical switch enters the bar state when the voltage is increased. At 28V, the micromirror is fully retracted. When the voltage is decreased, the micromirror does not spring back until the voltage drops to 18V. The cross state requires 30V to push the micromirror fully into the optical path, which is approximately the voltage required for the bar state. (Marxer et al., 1997, p. 283)

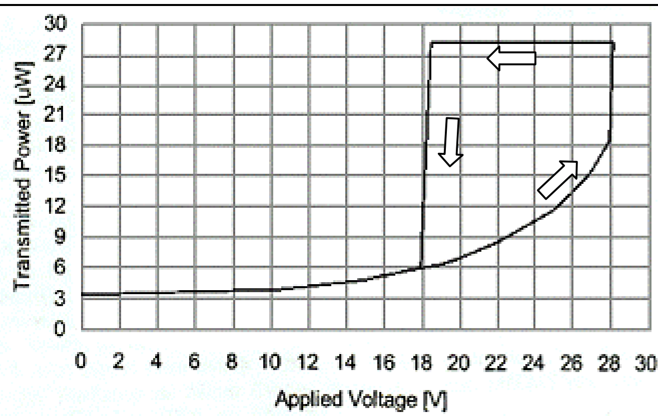


Figure 10: Transmitted power as a function of voltage applied on the outer comb drive (adapted from Marxer et al., 1997, p. 283)

F. V-Grooves

In micro-optical systems, v-grooves are used for holding and aligning optical fibers. To obtain good coupling efficiency, high-precision alignment of optical elements is necessary (Strandman and Bäcklund, 1997, p. 35). Hence, v-grooves are an important feature of the Marxer et al. optical switch. The v-grooves in the Marxer et al. optical switch are fabricated the same way as the other structures.

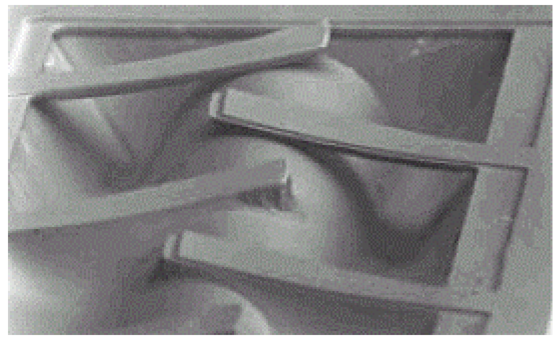


Figure 11: Holding structures for mounting optical fibers (adapted from Strandman and Bäcklund, 1997, p. 38)

Strandman and Bäcklund (1997, pp. 35-39) have said that incorporating holding structures such as those shown in Figure 11 would "substantially facilitate the mounting of [the optical fibers] in the aligning v-grooves. Certain structures could even force the fibers down into position in the aligning v-grooves, resulting in fixation of the fibers." The holding structures can be fabricated together with the v-grooves in the same step, and the holding structures would enable faster and proper mounting of the optical fibers. When the optical fibers are pushed into the v-grooves, the holding structures are bent upwards. Then, the holding structures clamp down on the sides of the optical fibers, and they allow the optical fibers to self-align in the v-grooves.

G. Insertion Loss

Insertion loss for an optical fiber system is defined as the total optical power loss caused by insertion of an optical component. If P_1 is the optical power delivered to that part of the optical fiber following the inserted optical component, and P_0 is the optical power delivered to that same part of the optical fiber before insertion of the optical component, then the insertion loss is often given as a ratio in dB:

$$\text{Insertion loss } = 10\log_{10}\left(\frac{P_0}{P_1}\right)$$

(American National…, 2000) The insertion loss of a MEMS optical switch is an important measure of its efficiency at coupling an optical signal from one optical fiber to another. The insertion loss of a two-dimensional 2x2 MEMS optical switch in the bar state is not the same as in the cross state. The Marxer et al. optical switch exhibited an insertion loss of 0.6-1.6 dB in the bar state, and 1.4-3.4 dB in the cross state (Marxer et al., 1997, p. 282). Additional losses are introduced when the light beam is reflected off the micromirror in the cross state. These losses due to the micromirror have been discussed in the section on micromirrors. Two effects that contribute to the insertion loss of a MEMS optical switch, and are present in both states are Fresnel reflection and beam divergence. These effects are discussed below.

(a) Fresnel reflection

Fresnel reflection occurs at the boundary between glass and free-space as the light beam exits and enters an optical fiber (Marxer et al., 1997, p. 278). Fresnel reflection refers to the reflection of part of the incident light at the sharp boundary between two media with different refractive indices (American National…, 2000). To determine the optical power loss caused by Fresnel reflection, the portion of incident optical power reflected is found using the formula:

$$\text{Reflected power } = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

where n_1 is the refractive index of the medium that the light is originally traveling in and n_2 is the refractive index of the medium that the light is entering (Crisp, 2001, pp. 51-53). For free-space MEMS optical switches, $n_1 = 1.5$ and $n_2 = 1.0$ when the light is leaving the optical fiber, and n1 = 1.0 and n2 = 1.5 when the light is re-entering the optical fiber. In both cases, the percentage of reflected power is 4%. Thus, considering Fresnel reflection alone, only about 92% of the original optical power is transmitted successfully, giving rise to a loss of about 0.362 dB.

(b) Beam divergence

As the light beam exits the optical fiber, it begins to spread. The optical power loss due to this spreading may be estimated using mode coupling theory. Light is an electromagnetic wave, and a mode is a "pattern of electric and magnetic fields having a physical size" (Crisp, 2001, p. 61). Figure 12 illustrates mode coupling between two optical fibers. (a) shows two single mode optical fibers, which propagate only one identical mode of light. When the light beam exits the optical fiber on the left, it begins to spread. The electric

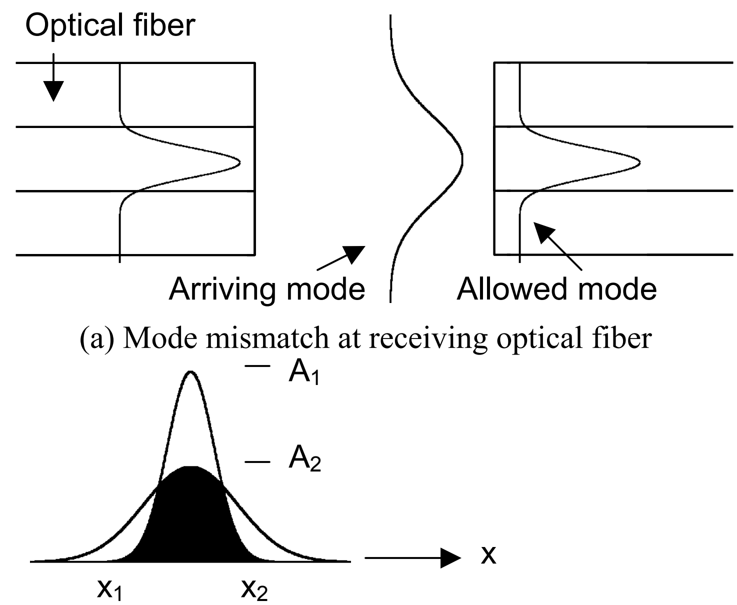


Figure 12: Mode coupling between optical fibers
(adapted from Pollock, 2001)

and magnetic field patterns change, resulting in a different mode arriving at the receiving optical fiber. For simplicity, the modes are approximated by Gaussian profiles. According to coupling mode theory, the amount of optical power coupled into the receiving optical fiber is given by the overlap integral of the arriving and allowed modes. The overlap region is shown in (b). If the receiving optical fiber allows an amplitude A_1 and beam radius w_1, and the arriving beam has amplitude A_2 and beam radius w_2, then the overlap integral is

$$\int_{x_1}^{x_2} A_1 e^{-x^2/w_1} A_2 e^{-x^2/w_2} dx$$

The discussion here is restricted to one dimension, and it is assumed that there is no phase shift present in the arriving light wave. (Crisp, 2001, p. 61; Pollock, 2001) For a more complete discussion of coupling mode theory, see chapters ten and eleven of *Fundamentals of Optoelectronics* by Pollock.

The mode mismatch is a major cause of light loss at the receiving optical fiber. Typically, lenses are used to contain the divergence and refocus the beam (Pollock, 2001). According to Juan et al. (1998, p 208), the diameter of the beam can increase from 10 to 22 μm for light of wavelength 1.55 μm, over a distance of 100 μm. The micromirror area has to be greater than 100% the beam size to accommodate the spread. However, with microlenses, the micromirror size can be much smaller.

Another cause of light loss is misalignment of the optical fibers. However, losses due to misalignment are reduced by using v-grooves to position the optical fibers.

H. Other Two-Dimensional MEMS Optical Switches

The Marxer et al. optical switch uses a sliding vertical micromirror. Other novel two-dimensional MEMS optical switches have been fabricated that use different micromirror designs. Lee et al. (1999, pp. 7-13) have fabricated a two-dimensional 2x2 MEMS optical switch based on a surface-micromachined, vertical torsion micromirror. The operation voltage of the vertical torsion micromirror is higher, at 80V for switching to the cross state and 54V for release from the cross state. The vertical torsion micromirror exhibits the same hysteresis effect seen in the Marxer et al. optical switch. The switching speed is also slower, at 0.4 ms. However, the insertion loss is lower at 1.25 dB in the cross state, and 0.55 dB in the bar state.

Pop-up micromirrors have also been used in two-dimensional MEMS optical switches. A pop-up micromirror is shown in (1) of Appendix C. The base of the mirror is pivoted on the silicon substrate. By means of hinged joints, the mirror is connected to a sliding plate. The mirror is pushed up when the sliding plate moves to the left. The mirror is laid flat when the sliding plate moves right. (2) illustrates the use of a number of pop-up micromirrors in a two-dimensional MEMS optical switch. An array of input and output optical fibers is arranged on the silicon substrate together with the pop-up micromirrors. Focusing optics is used to control beam divergence. An activated pop-up micromirror reflects the light beam whereas an unactivated micromirror does not. A two-dimensional 4x4 MEMS optical switch using this scheme has been fabricated by Lin (1998, p. 147). An operation voltage of 100V is required for the sliding plate, and the micromirror takes 0.5 ms to become upright and 0.56 ms to lie flat.

I. Applications of MEMS Optical Switches

MEMS optical switches were developed to replace the O-E-O switches. Hence, their applications are well-established. The smaller, low port count (2 to 32 ports) MEMS optical switches are used in optical add/drop multiplexers and in network restoration (Neukermans and Ramaswami, 2001, p. 66). Add/drop multiplexers are multiplexers that are "capable of extracting and inserting lower-rate signals from a higher-rate multiplexed signal without completely demultiplexing the signal" (Bates, 2001, p. 273). Network restoration takes place when the optical switch diverts the optical signal from the primary path that has failed, to the backup path (Rebello et al., 2001, p. 101). Synchronous Optical Network (SONET) for instance, is designed with ring architectures that provide two paths to any node. When one path fails, an optical switch can direct the optical signals to the alternative path. (Hecht, 2000, p. 189) MEMS optical switches of higher port count are used in optical cross connects (OXCs), which are large optical switches capable of simultaneously switching many input optical signals to any output ports. These OXCs usually employ the three-dimensional approach.

J. Advantages and Disadvantages of MEMS Optical Switches

MEMS optical switches have certain advantages over other types of switching technologies for all-optical networks.

(a) High-volume, low-cost production

MEMS technology uses many of the fabrication processes found in the semiconductor IC industry. Batch processing techniques whereby ICs are processed in batches, allow for a large number of ICs to be produced at one time, and the processing cost to be shared over many units, thus helping to lower manufacturing costs. The same batch processing techniques can be applied to fabricate MEMS optical switches; thus, MEMS optical switches can be manufactured cheaply and in large quantities. (Barthel and Chuh, 2001, p. 96; Neukermans and Ramaswami, 2001, p. 62)

(b) Compactness

MEMS is a technology for miniaturization. MEMS optical switches are therefore miniature switches that have lower space requirements. Furthermore, MEMS has the potential for highly integrated optics. Wu (1997, pp. 1836-1837) describes a Free-Space Microoptical Bench (FS-MOB) where micro-optical elements, micropositioners and microactuators are monolithically integrated on the same substrate. Surface micromachining techniques for MEMS allow entire functional optical systems to be produced on a single chip, greatly reducing the size and weight of the optical systems.

(c) Optical transparency

MEMS optical switches use micromirrors to directly alter the free-space propagation paths of light beams. Hence, MEMS optical switches operate independently of protocols, wavelengths, data rates, and modulation formats. The switching function is not affected by changes in these network properties, thus allowing for easy upgrades. (Bates, 2001, p. 145; Barthel and Chuh, 2001, p. 96)

However, MEMS optical switches also have limitations, most notably scalability to higher port counts. Optical switches of higher port counts are constructed by cascading smaller optical switches, often 1x2 switches. As more optical switches are cascaded together, the differences in lengths of the optical paths, through various switch configurations become more substantial. Differences in the propagation distance of light introduce varying amounts of light loss, thus making the switch behave differently in different states. (Morris, 2001, p. 49)

MEMS optical switches are mechanical devices even though they are at the microscale. They consist of machined moving parts controlled by electronics. Having moving parts raises the question of reliability as these parts could be worn out after some time. The long-term durability and robustness of MEMS optical switches has to be addressed for MEMS optical switches to be viable. (Hecht, 2001, p. 125-126)

Another potential problem for MEMS optical switches is the electrical connections for the micromirrors. According to Morris (2001, p. 49), "at least four electrical connections per mirror are needed [in the analog approach]. Thus thousands of electrical interconnects must come off the MEMS chip." Integrating all the addressing, control and drive electronics will be difficult, especially when high-voltage and precise analog circuitry is required (Morris, 2001, p. 49). The unwanted cross-talk among electrical connections must be kept to a minimum, in order to avoid errors in controlling the movement of the micromirrors.

VI. CONCLUSION

MEMS inherent advantages such as batch processing techniques, compactness, potential for integration with electronic circuits, together with the well-developed fabrication technology of the IC industry, make MEMS optical switches the dominant all-optical switch technology. However, MEMS optical switches have yet to gain widespread acceptance in industry. Even though MEMS optical switches such as Lucent Technologies' WaveStar™ Lambda Router, are available in the market, they have yet to be commercially successful (Yeow et al., 2001, p. 6). MEMS optical switches also face stiff competition from other all-optical switch technologies. These competing technologies range from the use of liquid crystals to bubbles, to perform the switching function. A notable example of the latter is the Agilent Champagne switch, in which a bubble at the intersection of two optical fibers switches the path of the light beam by total internal reflection (Morris, 2001, p. 50). The problems remaining in MEMS optical switches will have to be addressed before MEMS optical switch technology can become competitive, and commercially viable in the long term.

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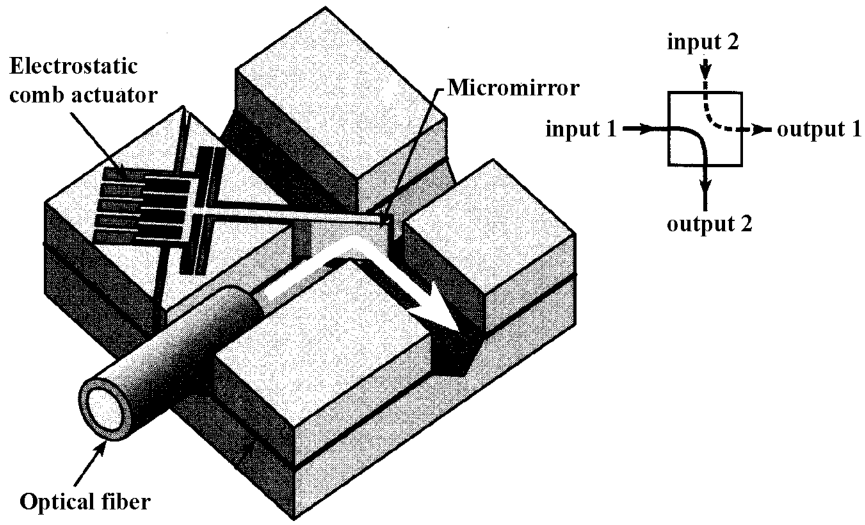
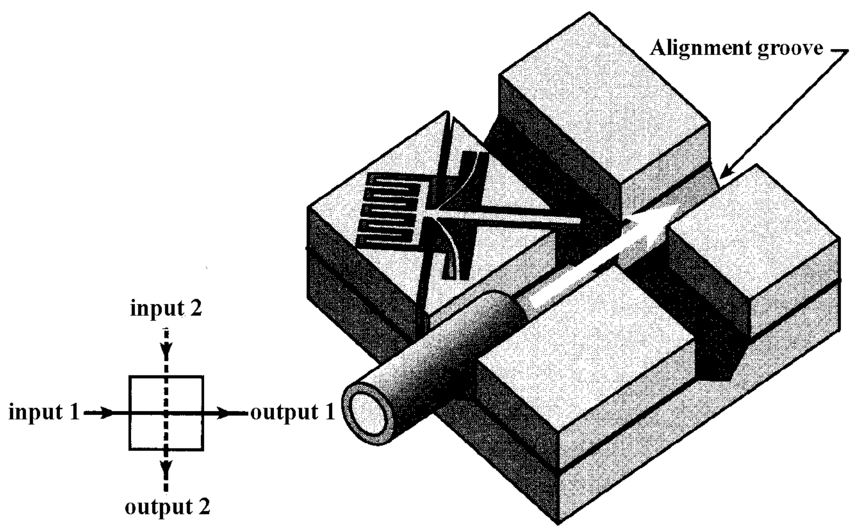
VIII. APPENDICES

Appendix A: Structure and operation of the Marxer et al. optical switch

(adapted from Maluf, 2000, p. 189)



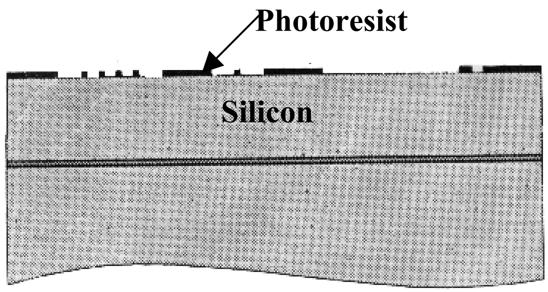
(1) Cross state



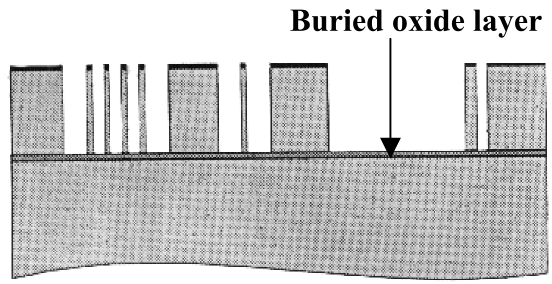
(2) Bar state

Appendix B: Fabrication of the Marxer et al. optical switch

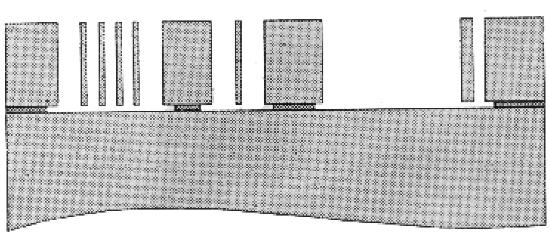
(adapted from Marxer et al., 1997, p. 280)



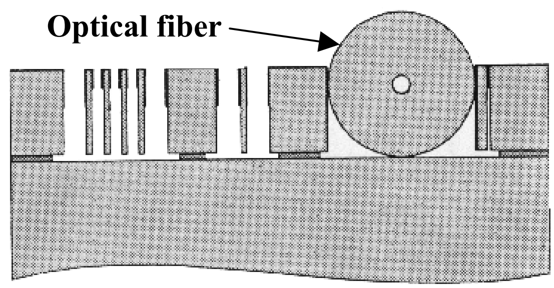
(1) Patterning



(2) Deep Reactive Ion Etching



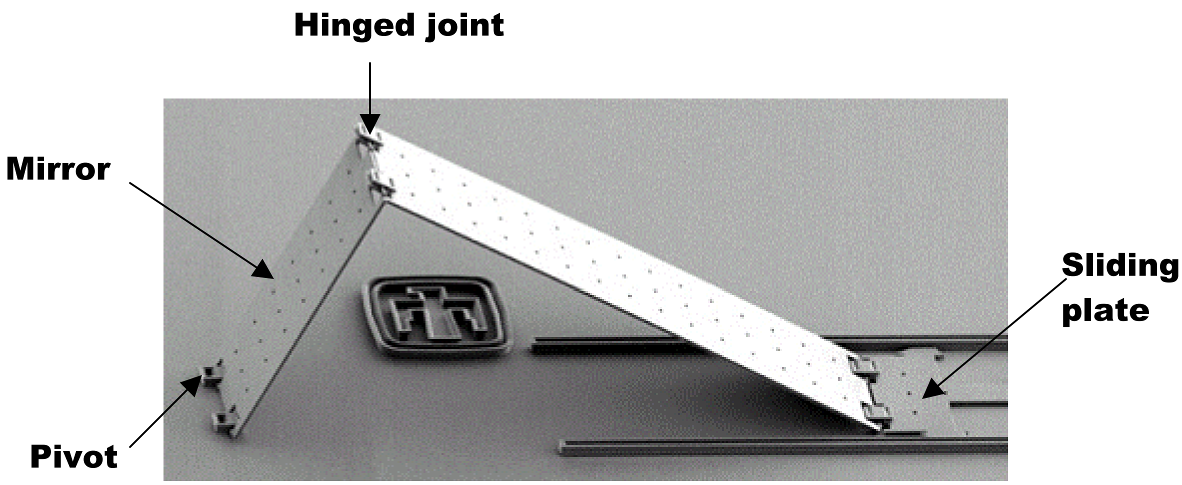
(3) Etching buried oxide



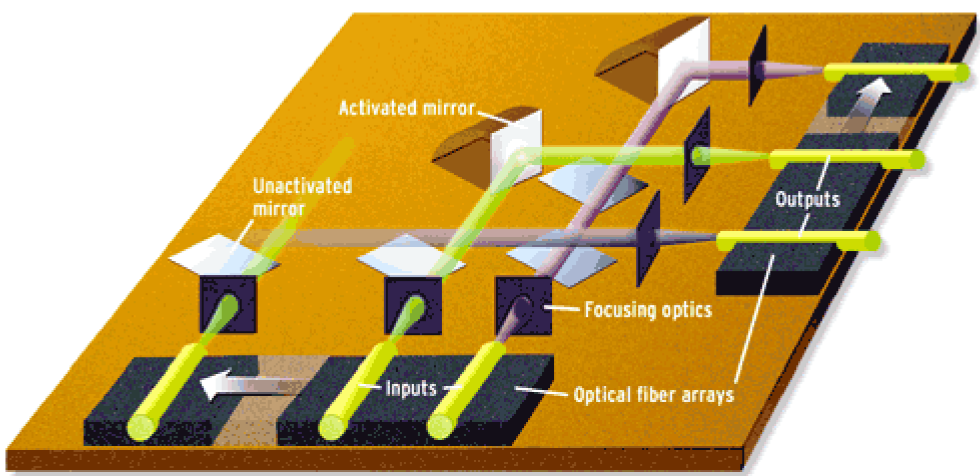
(4) Metal coating and assembly of fibers

Appendix C: Two-dimensional MEMS optical switch based on pop-up mirrors

(adapted from Sandia National Laboratories, 2001; Morris, 2001, p. 48)



(1) A pop-up micromirror



(2) Two-dimensional MEMS optical switch