Digital MEMS for Optical Switching

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ABSTRACT

Over the last few years an amazing amount of interest has emerged for applications of micro electro-mechanical systems (MEMS) in telecommunications. Silicon-based optical MEMS have proven to be the technology of choice for low-cost scalable photonic applications because they allow mass manufacturing of highly accurate miniaturized parts, and use materials with excellent mechanical and electrical properties. Applications include tunable lasers, optical switches, and tunable filters. The use of MEMS for optical switching has turned out to be most attractive since this application could revolutionize fiber optic telecommunications. In this article we discuss the technology, performance, and reliability of 2D MEMS optical switches. We show that this technology meets the scalability, performance, and reliability requirements for important applications in fiber optic networks.

INTRODUCTION: OPTICAL SWITCHING

The main attraction of optical switching is that it enables routing of optical data signals without the need for conversion to electrical signals, and therefore is independent of data rate and data protocol. Applications of optical switching include protection and restoration in optical networks, bandwidth provisioning, wavelength routing, and network performance monitoring. One of the key applications is optical crossconnects, which are the basic elements for routing optical signals in an optical network or system. Often the crossconnect is required to be strictly nonblocking, which means that any input can be switched to any output, and if a new connection is made, existing connections are not affected. In blocking switches some connections cannot be established for certain choices of input and output ports.

Most current "optical" crossconnects in fact use an electrical core for switching (sometimes referred to as OEO switching) where the optical signals are first converted to electrical signals, which are then switched by electrical means and finally converted back to optical signals. This solution is not future-proof since when the data rate increases, the expensive transceivers and electrical switch core have to be replaced.

All-optical crossconnects (sometimes referred to as OOO crossconnects) are much more attractive because of the avoidance of the conversion stages, and because the core switch is independent of data rate and data protocol, making the crossconnect ready for future data rate upgrades. Since there is no need for lots of expensive and power-hungry high-speed electronics, transmitters, and receivers, the system becomes less expensive; in addition, the reduction of complexity improves reliability and reduces the footprint of the OOO crossconnect compared to OEO solutions.

Besides OOO and OEO switches there are also opaque optical crossconnects (OEOEO) as a compromise between OEO and OOO approaches. The optical signal is here converted into electrical signals and then again to optical. The signals are switched in the optical domain and then converted to electrical and finally back to optical signals. This option may still improve the performance of the crossconnect since the optical switch core doesn't have the bandwidth limitations and power consumption of an electrical switch core. Opaque optical crossconnects allow the options of wavelength conversion, combination with an electrical switch core, quality of service monitoring, and signal regeneration, all within the crossconnect switch. But since there are OE and EO conversions, the data rate and data format transparency is lost. Within this article we only discuss pure all-optical switches.

ALL-OPTICAL SPACE SWITCH TECHNOLOGIES

Opto-mechanical technology was the first commercially available for optical switching. It is based on beam expanding collimators and electromagnetically (e.g., stepper motor or solenoid) actuated mirrors, prisms, or collimators. Opto-mechanical switches with very low insertion loss (< 1 dB) are currently available from several vendors. The switch configurations are limited to 1×2 and 2×2 port sizes. Larger port counts can only be obtained by combining several 1×2 or 2×2 switches, but this increases cost and degrades performance. Opto-mechanical switches are mainly used in fiber protection and very low port count wavelength add-drop applications.

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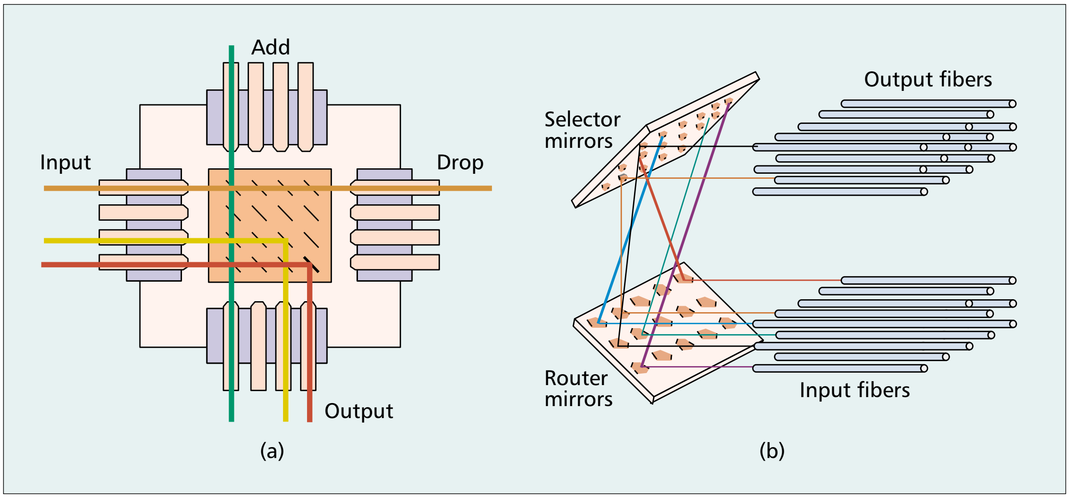


Figure 1. *MEMS approaches for optical crossconnect switching: a) digital or 2D MEMS technology; b) analog, scanning mirror, or 3D technology.*

Basically a MEMS device is a mechanical integrated circuit where the actuation forces required moving the parts may be electrostatic, electro-magnetic or thermal.

Optical switches made with silica-on-silicon waveguide or photonic lightwave circuit (PLC) technology [1] are based on the principle of thermally induced changes of the refractive index in silica-based waveguides. The local heating is obtained with thin-film heater electrodes above the waveguide. The technology has some disadvantages such as limited integration density (large die area) and high power dissipation. A commercially available PLC 8 × 8 crossconnect switch dissipates about 4 W, requiring forced air cooling for reliable operation. Optical performance parameters such as crosstalk and insertion loss may be unacceptable for some applications. On the positive side, this technology allows the integration of variable optical attenuators and wavelength selective elements (arrayed waveguide gratings) on the same chip with the same technology.

Lithium niobate technology [2] is also based on local refractive index changes in dielectric waveguides. In this case the index change is obtained by the electro-optic effect (similar to external modulators for high-speed optical modulation). This technology is special since it is one of the few that enable very fast switch times (nanoseconds) allowing optical packet switching. Unfortunately it has the same disadvantages of other waveguide switches: limited scalability, high insertion loss, and high crosstalk.

Liquid crystal optical switches [3] are based on the change of polarization state of incident light by a liquid crystal by the application of an electric field over the liquid crystal. The change of polarization in combination with polarization selective beam splitters allows optical space switching. In order to make the devices polarization insensitive, some kind of polarization diversity must be implemented, which makes the technology more complex. Several manufacturers have been able to deliver low port count optical switches (1 × 2, 2 × 2) based on this principle. It is interesting to mention that this technology also allows wavelength dependent switching, attractive for wavelength add-drop applications.

In addition to the technologies mentioned above, many others have been developed for optical switching, but most of them are not yet commercially available, including III-V semiconductor-based waveguide switches, polymer-based thermo-optic digital waveguide switches, and semiconductor optical amplifier (SOA)-based gate switches.

MEMS-Based Optical Switches

Micro-electromechanical systems (MEMS) is rapidly establishing itself as the most attractive technology for optical switching since it allows low-loss large-port-count optical switching solutions at the lowest cost per port [4]. Basically a MEMS device is a mechanical integrated circuit where the actuation forces required to move the parts may be electrostatic, electromagnetic, or thermal. The basic technology is based on established semiconductor processes for manufacturing highly accurate miniaturized parts and uses materials with excellent mechanical and electrical properties (Si, SiOx, and SiNx). Silicon-based MEMS devices can be manufactured with different process technologies, including bulk micromachining, in which the mechanical structures are etched in single crystal silicon, and surface micromachining, in which epitaxial layers of polysilicon, silicon nitride, and silicon oxide are deposited, patterned, and selectively removed.

One can distinguish between two MEMS approaches for optical switching: 2D (digital) and 3D (analog) MEMS. In 2D MEMS the switches are digital since the mirror position is bistable (on or off), which makes driving the switch very straightforward. Figure 1a shows a top view of a 2D MEMS device with the MEMS mirrors arranged in a crossbar configuration to obtain crossconnect functionality. Collimated lightbeams propagate parallel to the substrate plane. When a mirror is activated, it moves into the path of the beam and directs the light to one of the outputs since it makes a 45° angle with the beam. This arrangement also allows light to be passed through the matrix without hitting a mirror. This additional functionality can be used for adding or dropping optical channels.

> *Another key element is that during switching the actuator is freely moving in the air and is not in contact with the substrate except with the single contact point when it lands in its final position. The non-contact movement eliminates friction and wear of the MEMS structure.*

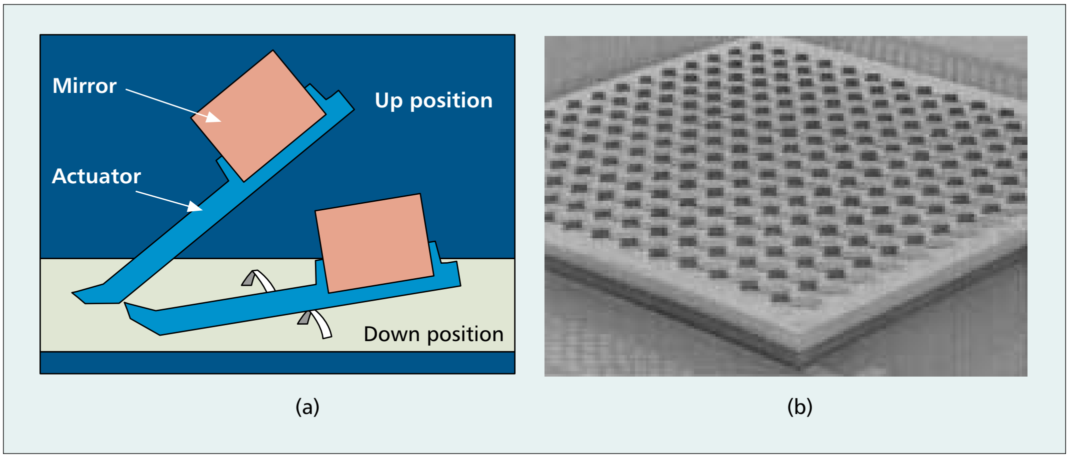


Figure 2. *Digital MEMS design: a) schematic of basic mirror/actuator element for 2D optical switches; b) SEM image of a 16 × 16 crossconnect switch MEMS die with 256 mirror/actuator elements.*

In 3D MEMS (Fig. 1b), a connection path is established by tilting two mirrors independently to direct the light from an input port to a selected output port (router/selector architecture). This is a most promising technology for very large-port-count optical crossconnect switches with > 1000 input and output ports. Potentially, losses as low as 3 dB can be obtained. A drawback of this approach is that a complex (and very expensive) feedback system is required to maintain the position of the mirrors (to stabilize the insertion loss) during external disturbances or drift.

2D MEMS Technology: A Mature Technology Today

Here we go deeper into 2D MEMS technology. We address MEMS, optical design, and packaging, as well as optical performance and reliability. As it turns out, all those aspects are closely related.

MEMS Design Aspects — The basic parts of 2D MEMS optical switches are moving MEMS mirrors; they must have a sufficiently large size and movement range. This means that the MEMS actuator needs to provide a repeatable traveling distance of several hundred microns in order to switch the mirrors completely in and out of the optical beam while maintaining highly accurate and repeatable mirror angles and minimizing switch transient effects to minimize switch time.

Furthermore, the MEMS design must be optimized so that the resonance frequency of the structure is sufficiently high to make the device insensitive to external mechanical vibration and shock. Finally, a small footprint of the basic switch structure is required to reduce the propagation distance of the light, which is advantageous for optical design.

Many different actuator mechanisms have been investigated for digital optical switches including comb drives, thermal expansion actuators, and electrostatic scratch drive actuators [5]. Unfortunately, these approaches have insufficient movement range, cannot maintain a small footprint, or are considered unreliable.

We found that the most suitable design is the gap-closing electrostatic actuator [6] shown in Fig. 2a. It is designed so that in the off state it makes an angle relative to the substrate. When a voltage is applied between the actuator and the substrate electrode, the electrostatic attraction force moves the actuator downward. The highly reflective gold-coated mirror attached to the actuator is assembled so that it makes an angle of 90° with the substrate.

The extension of the actuator arm on which the mirror is attached provides the large motion range for the mirrors. It is important to mention that during the actuator movement, the angle of the mirror is not affected and always remains perpendicular with the substrate.

In order to stop the mirror during its downward movement and prevent electrical shorting with the substrate, a special stopping element is positioned under the actuator. Because of the flatness of the actuator and the bending of the stopping element, the actuator will contact the stopping element at a single point. This is one of the key elements for reliability of the switching element. Another key element is that during switching the actuator is freely moving in the air and not in contact with the substrate except at the single contact point when it lands in its final position. The noncontact movement eliminates friction and wear of the MEMS structure.

For the actuation, electrostatic actuation is most advantageous since it allows extremely low power dissipation, on the order of a few microwatts for a complete 16 × 16 crossconnect device.

Optical Design Aspects — The optics of a 2D optical crossconnect switch [7] consist of two collimator arrays, which are aligned with the mirrors on the MEMS die (Figs. 1a and 2b). A collimator is an optical element that transforms the optical mode of a single-mode fiber into a lightbeam with a given beam waist diameter.

The key optical performance parameter of an optical switch is insertion loss. The most important loss mechanisms for the 2D crossconnect switch architecture are:

- Path length dependent loss
- Loss due to angular mirror or collimator misalignment

- Loss due to clipping of light at the mirror boundaries

The path lengths for beams propagating from input collimator to output collimator vary depending on which connection is established. This path length variation causes insertion loss, which can be described as axial misalignment of Gaussian beams and is a function of the beam waist radius ω and the size of the switch (e.g., for a 16 × 16 switch with a 1 mm^2 MEMS cell size the maximum path length difference is 30 mm).

Due to manufacturing imperfections, an array of micro-mirrors may have mirror angle non-uniformities of the order of ±0.1 deg. This will cause angle non-uniformities of the reflected beams, which in-turn result in associated coupling losses. These losses can be described as angular misalignments of Gaussian beams and is proportional with the squares of both the beam waist radius and the angular non-uniformity. The sum of both axial and angular misalignment losses can be minimized by selecting the optimum beam waist radius for the collimated beam for a given beam angle non-uniformity. In order to avoid clipping losses, a mirror size has to be selected with respect to this optimum beam waist size. The collimators are not only designed with tightly specified optical beam parameters, but must in addition also meet other optical requirements such as low back reflection, low polarization dependent loss, and low wavelength dependent loss.

Packaging Design Aspects — A hermetic housing is required to protect MEMS and optics from the outside environment, since MEMS are sensitive to dust particles and humidity. Humidity can cause a number of failure mechanisms such as anodic oxidation [8] and condensation of moisture on the MEMS and optics. Hermetic sealing of housings with many fiber feedthroughs (a 16 × 16 optical crossconnect switch has 32 fibers going through the wall of the housing) is a technical challenge. True hermetic seals (preventing permeation of humidity) can only be obtained with perfect metallic seals around the fibers. The packages must also be designed so that they can accommodate differences in thermal expansion between the different parts inside and reduce the influence of thermal excursions on the optical performance. Finally, the package has to provide the feedthrough for the electric signals toward the electronic driving circuits and the MEMS chip inside the housing (Fig. 3).

Optical Performance of 2D Crossconnect Switches — The key performance parameters of optical switches are insertion loss, crosstalk, repeatability, polarization dependent loss, switch time, and return loss. Insertion loss is especially critical since any additional loss increases the system cost (through additional optical amplification and/or more sensitive receivers, more frequent regeneration, etc.). Low polarization dependent loss (PDL) is required to minimize monitoring and dynamic compensation requirements. Other parameters such as crosstalk and back reflection also have an impact on the signal integrity in the network. Both switch time and repeatability are specific for optical switches. Switch time is defined as the time elapsed between the moment the command is given to the switch to change state until the moment the insertion loss of the switched path reaches more than 90 percent of its final value. This takes into account the time for the mirror to come into its on position as well as eventual settling time. Repeatability is defined as the difference between the maximum and minimum insertion loss of a path when the corresponding mirror goes through many consecutive switch cycles.

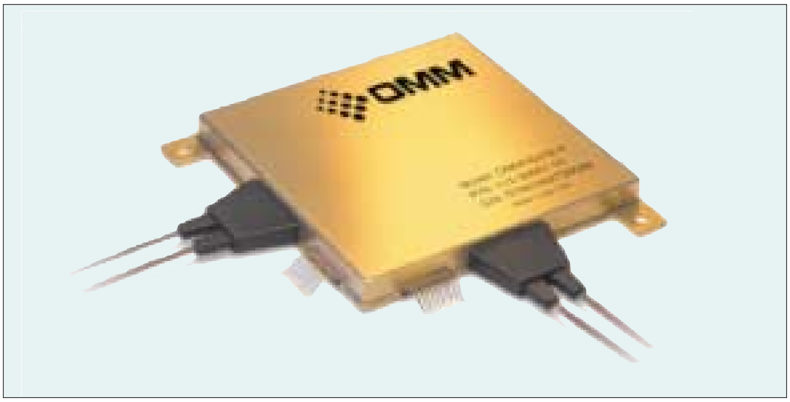


Figure 3. *Hermetic housing with 32 fiber feedthroughs for a 16 × 16 2D optical crossconnect switch.*

The optical performance of 2D optical crossconnect switches has been characterized thoroughly. Maximum insertion losses (over all possible connection paths) as low as 1.7 dB and 3.1 dB have been obtained for 8 × 8 and 16 × 16 2D crossconnect switches, respectively. Optical crosstalk and back reflection are less than –50 dB. The typical switch time is about 7 ms. Histograms of some key optical performance parameters of a typical 16 × 16 are shown in Fig. 4.

Reliability Assessment of 2D MEMS-Based Optical Switches — Reliability of MEMS structures strongly depends on the detailed design of those structures as well as the technologies used to fabricate them. However, a number of common potential failure mechanisms [8, 9] can be identified: mechanical wear, mechanical stress, dielectric breakdown, anodic oxidation, material migration, stress relaxation, contamination, and particles. Some of those mechanisms can be eliminated by proper design of the MEMS or housing, while others such as contamination and particles must be solved from the processing and manufacturing side. In addition to the silicon MEMS chip, other parts such as the collimator optics and hermetic housing may have an impact on component reliability. Proper design and choice of materials are crucial for high reliability.

Static reliability of a digital MEMS switch concerns the ability of the switch to alter states after it has remained for a longer time in the same state (e.g., a situation that may occur in optical protection switching). The associated failure mode is often referred to as *stiction*. Dynamic reliability (durability) of a MEMS switch

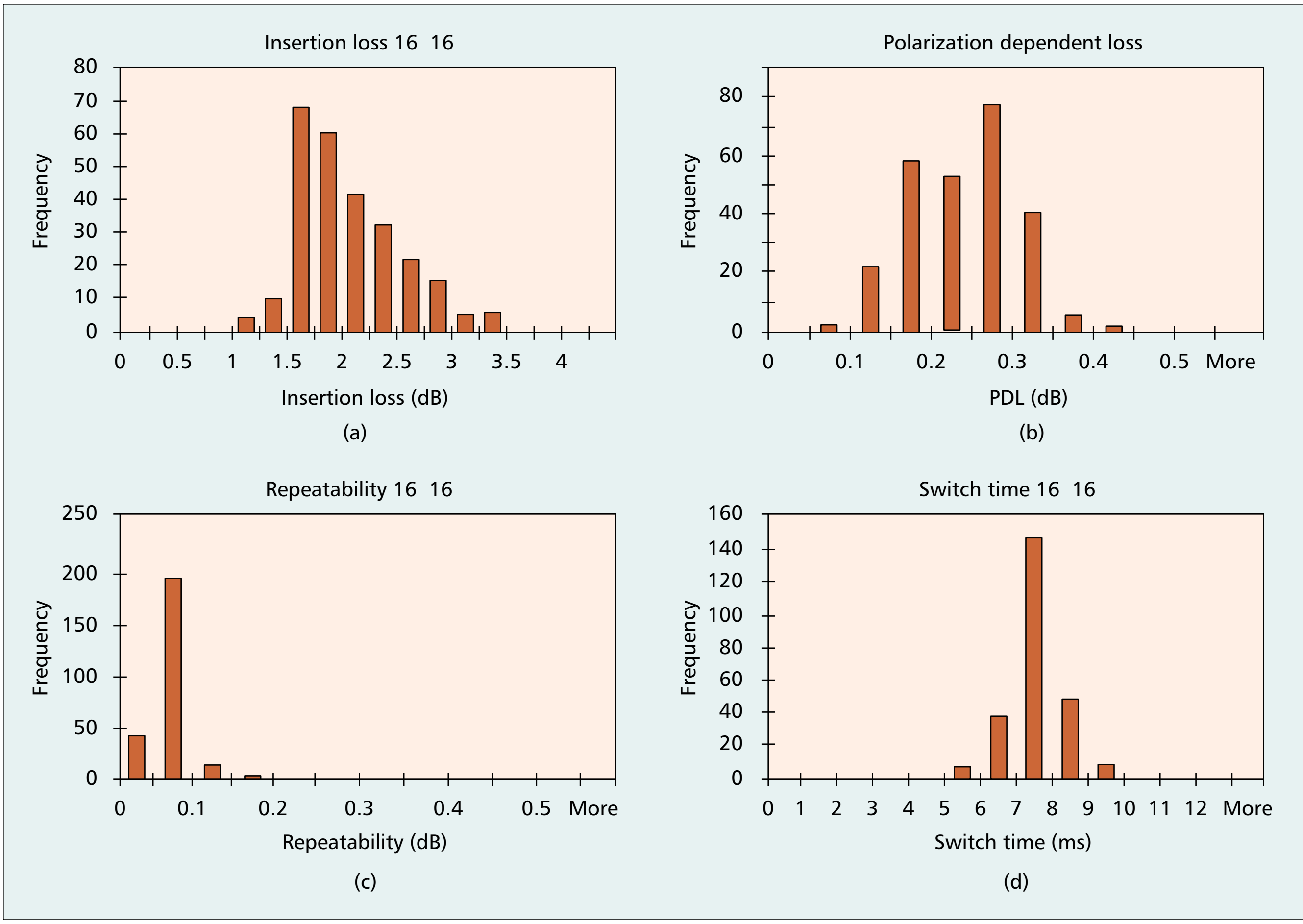


Figure 4. *Histograms of optical performance parameters over all 256 paths of a typical 16 × 16 digital optical crossconnect switch: a) insertion loss; b) polarization dependent loss; c) repeatability; d) switch time.*

concerns the ability of the switch to perform many switch cycles without wearout or degradation. Both static and dynamic reliability depend strongly on detailed design of MEMS structures.

In mechanical switches, failure during static operation (stiction) may occur due to the buildup of a parasitic adhesion force that prevents movement of the actuator. Several mechanisms may cause an adhesion force, including contamination, humidity, van der Waals forces, welding, and mechanical friction of parts. In 2D optical MEMS switches, stiction can be eliminated by designing the contact area to an absolute minimum (Fig. 2a), strict process cleanliness during manufacturing, and the use of hermetic housing.

Static reliability of the design shown in Fig. 4a has been verified for more than a year on over 4000 switch elements. No failures have been observed when the devices were altered in state; this leads to a verified estimate of < 37 FIT (1 FIT = 1 failure over 1 billion operating hours) for the random failure rate of the switching element. One million failure-free switch cycles are often required for dynamic reliability (equivalent with cycling every 10 minutes over a period of 20 years). Elimination of mechanical contact during movement solved this problem; excellent performance in excess of 10 million cycles has been verified for digital MEMS optical switches shown in Fig. 2a.

In order to qualify a technology for use in telecommunication systems, additional tests must be performed besides the static and dynamic reliability test. For those qualification tests Telcordia Generic Requirements [10] are often used as guidelines. These tests are perfectly suited to demonstrate the robustness of a fiber optic device under operation, storage, and transport conditions. Telcordia reliability tests have been performed on 2D MEMS-based digital crossconnect switches. An overview of the test conditions as well as some of the test results are shown in Fig. 5. The test results confirm that 2D MEMS technology meets telecommunications requirements.

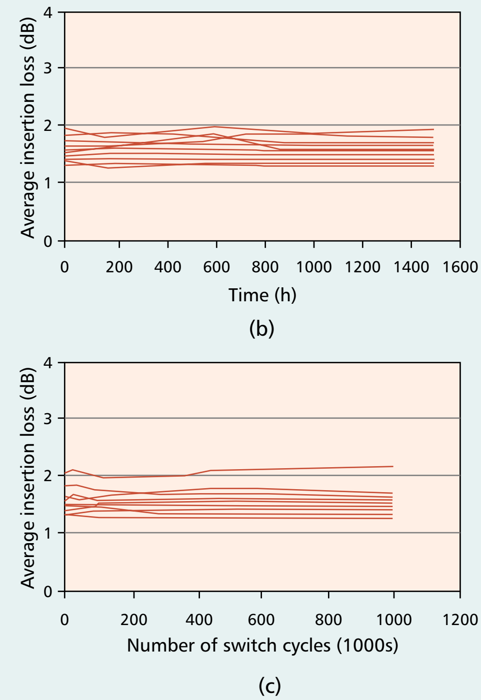
Applications of 2D MEMS Optical Switches

Optical crossconnects are the basic elements for routing optical signals in an optical network, and can be distinguished as fiber switch crossconnects and wavelength-selective crossconnects.

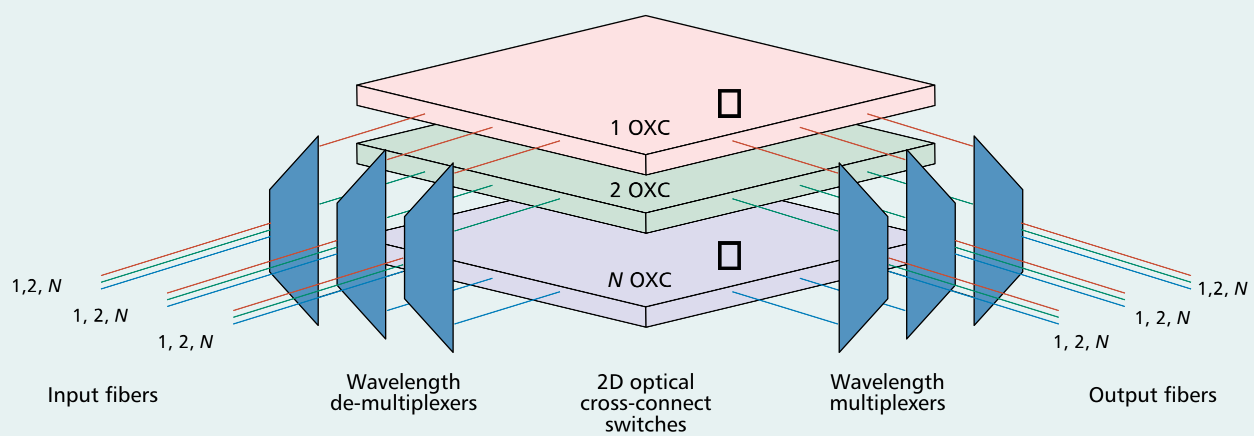
The fiber switch crossconnect (FSXC) allows switching of signals transmitted through the fibers without breaking them up into different wavelengths. This type of crossconnect switches whole bundles of signals and can be used for protection and routing applications, for example.

Endurance tests	
Damp heat	+75° C/90%RH, 1500 hours
Thermal cycling	-40° C/+85° C, 100 cycles
Thermal aging	+85° C, 2000 hours
Durability	1,000,000 cycles
Low temperature storage	-40° C, 2000 hours
Thermal shock	0° C /100° C, 20 cycles
Robustness tests	
Fiber retention	19.2 N, 10 s, 3 cycles
Fiber flex test	4.8 N, 100 flex cycles
Fiber twist test	4.8 N, 10 twist cycles
Mechanical shock	200 G, 1.3 ms, 5 shocks per direction: ±X, +/Y, ±Z
Mechanical vibration	10 to 55 Hz, amplitude 1.52 mm, 2 hours
Electrostatic discharge	500 V, human body model

(a)



■ **Figure 5.** *MEMS 2D crossconnect switch reliability verification: a) qualification tests for 2D MEMS; b) test results damp heat exposure (11 devices, 1500 hours at +75° C and 90% RH); c) test results durability (11 devices, up to 1 million switch cycles).*



■ **Figure 6.** *Wavelength Selective Cross-Connect (WSXC): The incoming fiber channels are demultiplexed, each wavelength goes to a specific NXN cross-connect switch. After switching, the wavelengths are multiplexed into the output fibers. The number of switches M is equal to the number of wavelengths and the port count N of the switches is equal to the number of incoming fiber channels.*

By arranging 2D optical crossconnect switches in a Clos network [11] large-size crossconnects (up to 512×512) can be built.

The wavelength-selective crossconnect (WSXC) (Fig. 6) allows switching of selected wavelengths from one fiber to another. In this application the crossconnect switch is combined with wavelength-selective elements, which demultiplex the incoming optical signals. Each wavelength is switched in a separate $N \times N$ crossconnect switch. This type of crossconnect allows provisioning and control of wavelength services and therefore more flexibility than the FSXC.

WSXCs can be scaled in a straightforward manner: each time a wavelength is added, an extra $N \times N$ switch is added, meaning that the crossconnect can be extended. WSXCs as large as 640×640 can easily be built for configurations with 40 wavelengths and 16 incoming fibers.

In addition to optical crossconnects, the 2D MEMS platform can also be used to obtain other functionalities by arranging the mirrors differently, and clever use of add and drop ports [12]. Functionalities such as $N \times M$, $2 \times N$, $1 \times N$, arrays of 1×2, and arrays of 2×2 can be built as well. These have applications in protection, service monitoring, and wavelength add-drop multiplexing.

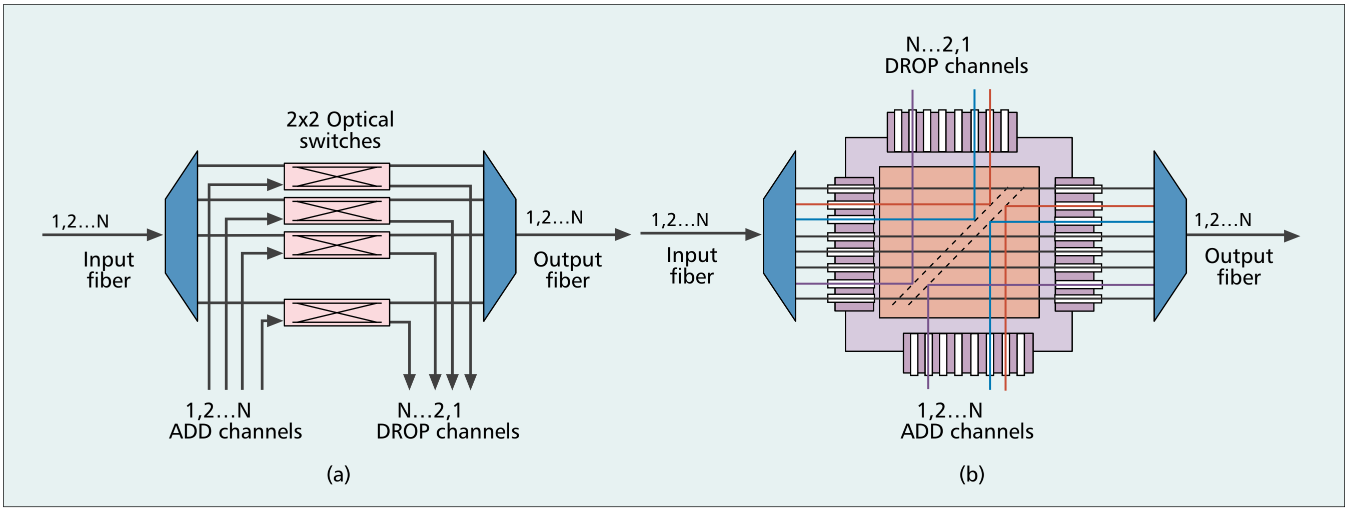


Figure 7. *a) Basic principle of Reconfigurable Wavelength Add-Drop Multiplexing; b) Implementation using 2D MEMS.*

A *reconfigurable wavelength add-drop multiplexer* (Fig. 7a) is an important element in optical network nodes. It consists of a wavelength demultiplexer splitting the wavelength signals from the input fiber over different fibers. An array of 2 × 2 switches allows dropping of one or more selected wavelength signals. At the same time a new signal can be added into the data stream. The signals are then routed back to a wavelength multiplexer and combined in the output fiber.

Using a 2D MEMS approach the arrays of opto-mechanical 2 × 2 switches can be replaced by a single MEMS device (Fig. 7b). The MEMS chip has two rows of mirrors, which operate simultaneously. When a mirror pair is activated, the incoming signal is routed to the drop port and the corresponding add port is coupled to the output port; otherwise, the light goes straight from the input to the output collimator. This solution has a considerably smaller footprint than the opto-mechanical approach. In addition all the fibers of the functional ports (input, output, add, and drop) are grouped together, greatly simplifying fiber handling and routing during installation.

Reliability and availability of the optical network are very important; therefore, redundancy is often built into the network. For certain key optical network elements a 1:1 redundancy is used so that for each element there is a corresponding protecting element. The switchover between a faulty network element and the protecting element can be obtained using an array of 1 × 2 switches or 1 × 2 splitters (this option has a higher loss). One can reduce the cost by implementing an *N*:1 shared protection (the *N* working units share only one unit for protection) scheme as shown in Fig. 8a, where two 1 × *N* switches route the signal through the protection unit.

Another application for 1 × *N* switches is shared monitoring. Proper operation of the optical network and network elements must be verified regularly, which requires tapping the optical signal from the signal line and routing it to diagnostic test equipment, which can be done with arrays of 1 × 2 switches or 1 × 2 splitters. By using an *N* × 1 optical switch, the number of expensive test equipment units can be reduced to one, as shown in Fig. 8b.

Conclusion

In the last few years a number of promising photonic switching technologies have emerged, but MEMS have been widely recognized as providing key advantages in functionality, insertion loss, scalability of switch fabric size, optical wavelength range, power dissipation, and ease of operation. 2D optical MEMS technology can deliver reliable and manufacturable switch engines for a whole range of applications including medium- and large-size optical crossconnects, wavelength selective optical crossconnects, wavelength add-drop multiplexing, optical service monitoring, and optical protection switching. In the future, the free space optic elements used in the 2D MEMS platform will be combined with other optical functionalities, such as integration with wavelength selective elements, integration with optical monitoring elements, active and passive optoelectronic devices, and integrated driving electronics. This will result in highly integrated, low-cost, and small-footprint devices for advanced fiber optic switching applications.

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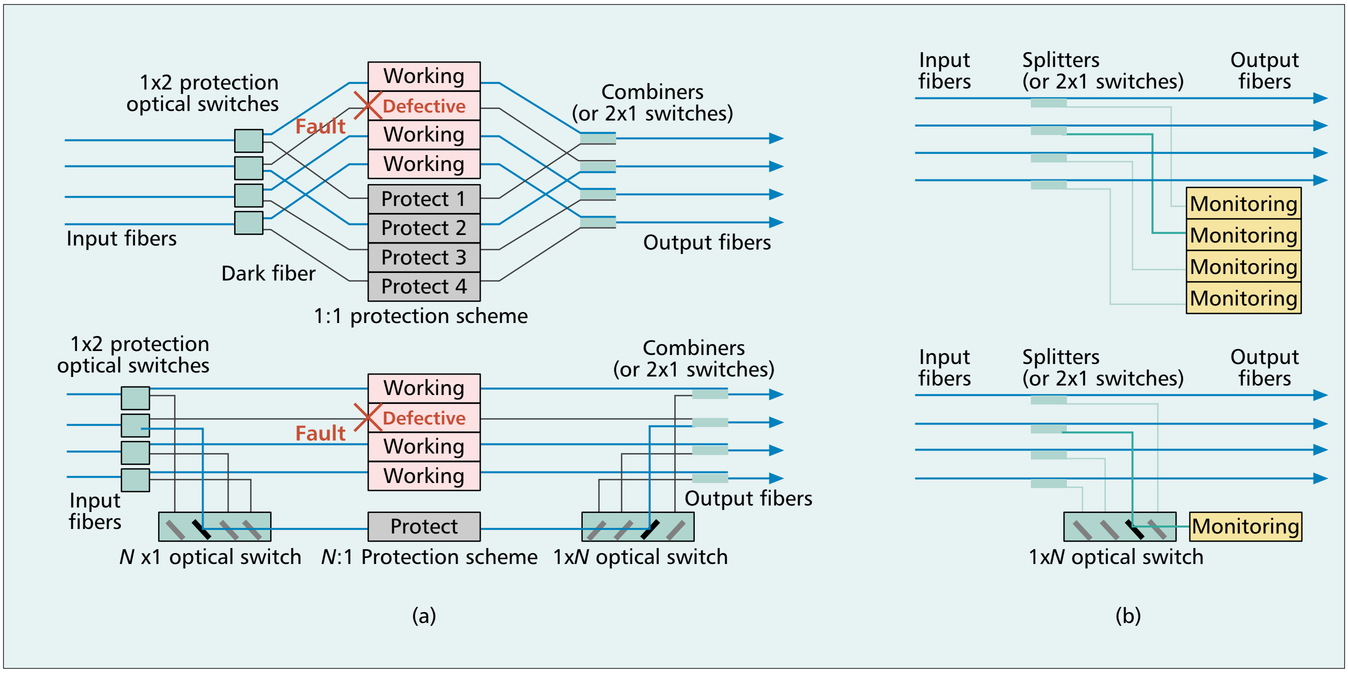

Figure 8. *Applications of* $1 \times N$ *switches: a) shared protection; b) shared monitoring.*

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Biographies

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