MEMS: The Path to Large Optical Crossconnects

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ABSTRACT

Continuous growth in demand for optical network capacity and the sudden maturation of WDM technologies have fueled the development of long-haul optical network systems that transport tens to hundreds of wavelengths per fiber, with each wavelength modulated at 10 Gb/s or more. Micro-electromechanical systems devices are recognized to be the enabling technologies to build the next-generation cost-effective and reliable high-capacity optical crossconnects. While the promises of automatically reconfigurable networks and bit-rate-independent photonic switching are bright, the endeavor to develop a high-port-count MEMS-based OXC involves overcoming challenges in MEMS design and fabrication, optical packaging, and mirror control. Due to the interdependence of many design parameters, manufacturing tolerances, and performance requirements, careful trade-offs must be made in MEMS device design as well as system design. In this article we provide a brief overview of the market demand, various design trade-offs, and multidisciplinary system considerations for building reliable and manufacturable large MEMS-based OXCs.

INTRODUCTION

To meet the growing demand for high data bandwidth, service providers are building optical networks around the globe using the latest wavelength-division multiplexed (WDM) technologies with mesh network architecture [1]. Lightpaths between access points in a network are created using fiber links containing many wavelength channels in each fiber, where each channel or port can have a data rate of up to 2.5 or 10 Gb/s. At the edge of the networks are the clients (IP/ATM routers, optical add-drop multiplexers, etc.) that use these lightpaths as high-capacity pipes for data/voice traffic. Data rate per port is expected to continue to increase (40 Gb/s in the very near future). The number of wavelength channels (or ports) per fiber will also continue to rise as WDM technologies mature.

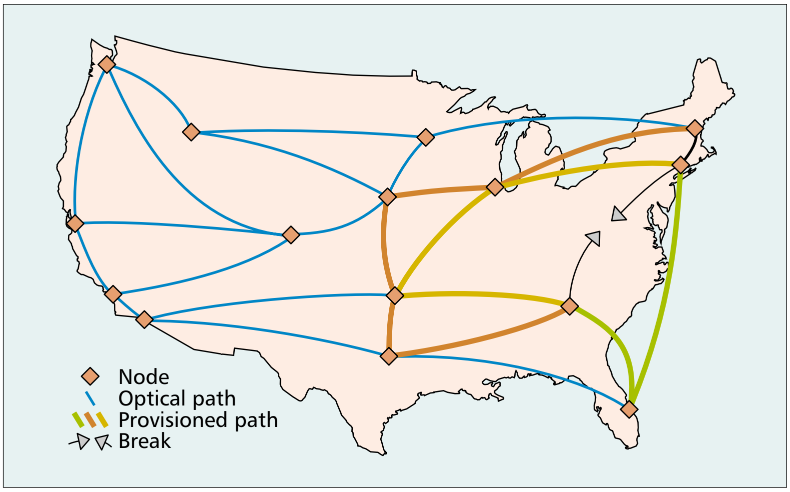
For long-haul core networks, core switching is needed for two main purposes: network provisioning and restoration (Fig. 1). Provisioning occurs when new data routes have to be established or existing routes modified. A network switch should carry out reconfiguration requests over time intervals on the order of a few minutes. However, in many core networks today, provisioning for high-capacity data pipes (OC-48 — 2.5 Gb/s and OC-192 — 10 Gb/s) requires a slow manual process, taking several weeks or longer. High-capacity reconfigurable switches that can respond automatically and quickly to service requests can increase network flexibility, and thus bandwidth and profitability.

On the other hand, restoration must take place in events of network failures (e.g., an accidental cable cut). A network switch needs to reroute traffic automatically in a time interval on the order of 100 ms, thus restoring operation of the network. Traditionally, network restoration is performed primarily by digital electronic cross-connects and synchronous optical network (SONET) add-drop multiplexers, operating at a data rate of about 45–155 Mb/s. For switches in a core network handling hundreds of gigabits per second of traffic, restoration at a coarser granularity is desirable in terms of both cost and manageability. Provisioning and restoration at coarse granularities also makes sense in light of the development of high-speed service-layer equipment such as IP routers with 10 Gb/s interface and Gigabit Ethernet.

These provisioning and restoration requirements of next-generation optical networks demand innovations in switching technologies. In the following sections, a vision and technologies for next-generation optical crossconnects (OXCs) are described, with a focus on MEMS technologies as the leading choice for photonic switching. Key challenges associated with the development of MEMS-based OXCs are discussed. Finally, an outlook on MEMS-based OXC development and deployment is presented.

NEXT-GENERATION CROSSCONNECTS

An emerging vision of the next-generation crossconnects for optical networks is one that allows network reconfiguration in the optical layer (Fig. 2a): provisioning and restoration in large units (e.g., the wavelength). Since the number of wavelengths per fiber has already reached hundreds today (160 wavelengths for 10 Gb/s) and is expected to increase, the desired port counts for such OXCs are expected to be in the thousands, where scalability is a paramount concern. Such a switch must also operate in a fully nonblocking manner, where every input must be allowed to connect to every output with no restriction. In addition, insertion loss, physical size, polarization effects, and switching times are also critical considerations. Equipped with intelligent provisioning and restoration capabilities, the next-generation OXC must also meet the stringent telecommunication requirements with an operating lifetime of 20 years.



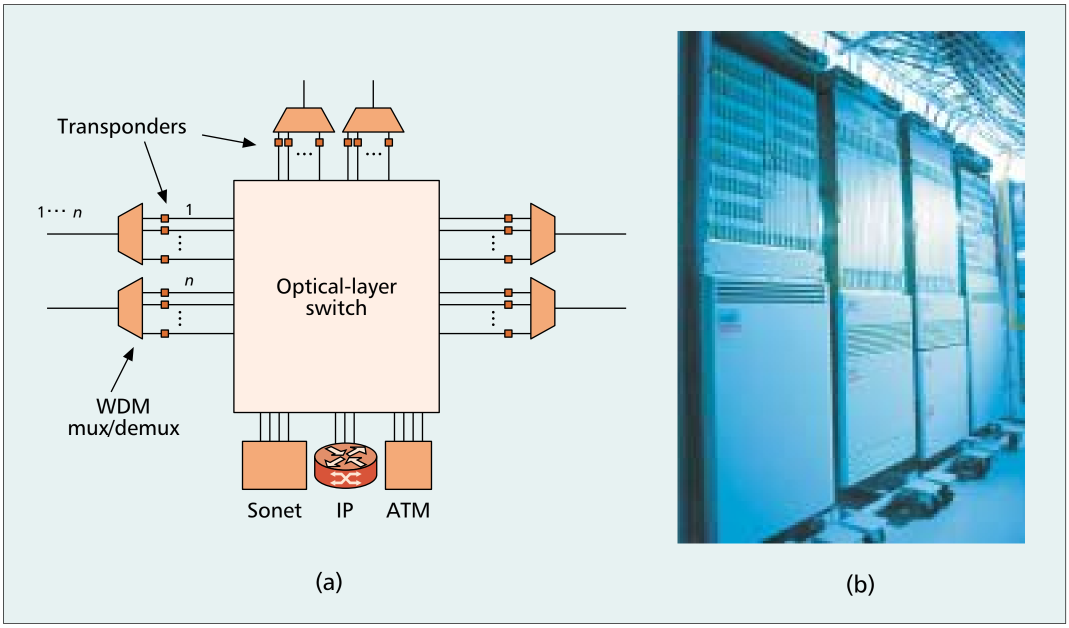
■ **Figure 1.** *Illustration of data path provisioning and restoration in a core transport mesh network.*

OPTICAL-LAYER SWITCH WITH AN ELECTRICAL SWITCHING CORE

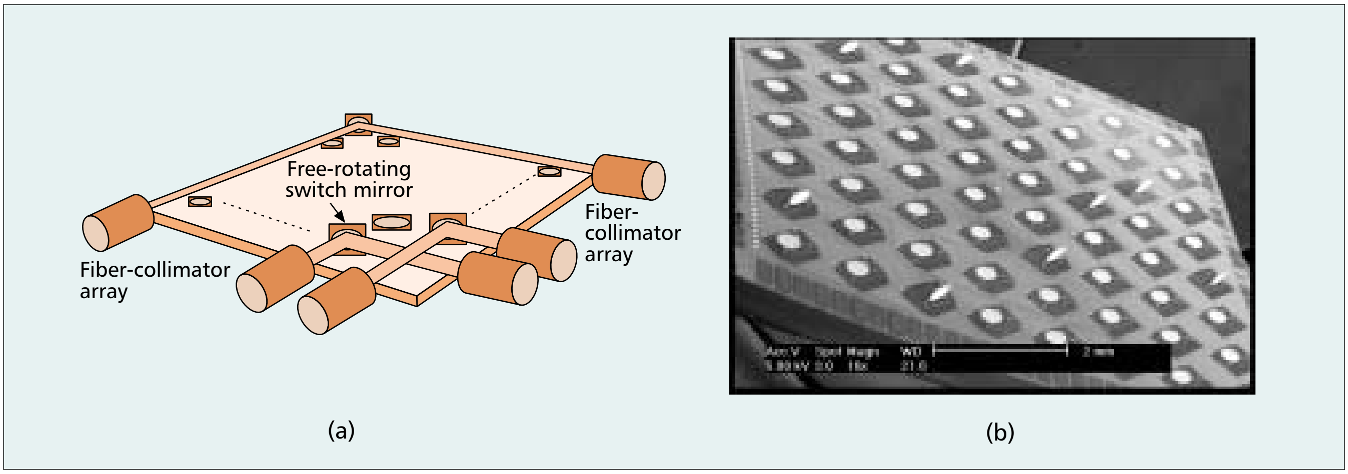
An optical layer switch can be implemented using opto-electronics interfaces and high-speed electronics. Due to the advancement of state-of-the-art integrated circuit (IC) technologies, multiple vendors currently offer electronics-based optical switches, also known as O-e-O (Optical-*electrical*-Optical) switches, with a few hundred 2.5–Gb/s ports residing in several equipment bays. These state-of-the-art switching systems provision and mesh-restore wavelengths at a granularity of 155 Mb/s to 2.5 Gb/s. For example, Fig. 2b shows Tellium's Aurora Optical Switch™ that has 512 OC-48 (2.5 Gb/s) input ports and 512 OC-48 output ports, and can deliver a total aggregate capacity of 1.28 Tb/s. They also provision and mesh-restore 10 Gb/s wavelengths (OC-192) via inverse multiplexing down to the basic switch rate, with the capability of grooming such subrate signals within a given 10 Gb/s pipe. Intelligence of this switch allows dynamic and automatic provisioning and protection as well as in-service system upgrades. Based on multiple stages of Clos structures [1], these switches are also scalable to thousands of switching ports.

OXCS WITH MEMS-BASED OPTICAL SWITCHING CORE

OXCs with electrical switching cores like the Aurora Optical Switch will continue to be deployed and remain in service for quite some time. Higher-speed and higher-capacity electronics switches are expected to reach the market in the near future as IC technology advancement



■ **Figure 2.** *a) Illustration of an optical-layer switch connected to DWDM transport systems and client equipment; b) Tellium's Aurora Optical Switch™ with 512 OC-48 (2.5 Gb/s) input ports and 512 OC-48 output ports, 1.28 Tb/s of aggregate switching capacity deployed, and carrying commercial traffic today.*



■ **Figure 3.** *a) Illustration of a 2D switching architecture; b) 2D* N × N *switches first demonstrated by AT&T [8].*

continues. On the other hand, the possibilities of improved scalability, footprint, manageability, and cost continue to fuel the quest for technological solutions beyond the proven state of the art. A new concept that has arisen is an all-optical OXC: an optical-layer switch with an optical switching core. All-optical switches are also known as *O-o-O* (Optical-*optical*-Optical) switches, which can be realized using arrays of MEMS-fabricated micro-mirrors.

MEMS for Photonic Switching — MEMS technology enables the fabrication of actuated mechanical structures with fine precision that are barely visible to the human eye. MEMS devices are by nature compact and consume low power. A batch fabrication process allows high-volume production of low-cost devices, where hundreds or thousands of devices can be built on a single silicon wafer. While the MEMS field is young compared to traditional semiconductor electronics, MEMS technology is based on fabrication technology fundamental to IC fabrication and many mature engineering disciplines such as mechanics, electromagnetics, and material science. Applied research in MEMS over the past two decades has led to numerous successful commercial devices, including valves and pressure sensors for automotive and medical applications, accelerometers, and angular rate sensors for airbags, toys, and instrumentation on land, at sea, in air, and in space. On the other hand, technological wonders such as injectable micromachines performing heart surgery inside the human body will remain fantasies of fiction writers for many decades to come.

Optical MEMS, nevertheless, is a promising technology to meet the optical switching need for large-port-count high-capacity OXCs. Within the last decade, the realization that tiny micromachined structures can steer light by generating small tilting motions has opened doors to many exciting applications of MEMS in photonic switching [2–4]. Current (nonelectronics) competing technologies for building are thermal bubble switches, which make use of total internal reflection and index-matched fluid, and waveguide-based switches, which make use of interferometric effects of light in planar waveguides. Potential benefits of an all-optical MEMS-based OXC include scalability, low loss, short switching time, low power consumption, low crosstalk and polarization effects, and independence of wavelength and bit rate. Therefore, MEMS has become the leading choice of technology for building large all-optical OXCs.

The most notable commercial MEMS optical devices to date are Texas Instruments' Digital Mirror Devices (DMD) [5], which have found applications in consumer visual display and projectors. While different MEMS-based solutions for critical transmission applications such as gain equalization [6] and dispersion compensation [7] are under investigation, add-drop multiplexers and small protection switches are among MEMS-based optical products that are slowly reaching the market. In recent news, small optical switch products have been announced to pass rigorous Telcordia telecommunications specifications, beginning to cast away healthy doubts about the long-term reliability of MEMS devices. Large MEMS-based OXCs as fully qualified products are expected to be a reality in the near future.

Two-Dimensional MEMS Switches — The OXCs of main interest are fully nonblocking optical switches with N input and N output ports. Two architectures for MEMS-based OXCs have emerged. In the first architecture, often known as 2D switching (Fig. 3) [2, 8, 9], a square array of $N \times N$ mirrors is used to couple light from a linear array of N fibers on one side of the square to a second linear array of N fibers on an adjacent side of the square. The (i, j) mirror is raised up to direct light from the ith input fiber to the jth output fiber. Mirror control for these 2D switches is binary and thus straightforward, but the trade-off of this simplicity is optical loss. While the path length grows linearly with N, the number of ports, the optical loss also grows rapidly due to the Gaussian nature of light. Therefore, 2D architectures are found to be impractical beyond 32 input and 32 output ports. While multiple stages of 32 × 32 switches can theoretically form a 1000-port switch, high optical losses also make such an implementation impractical.

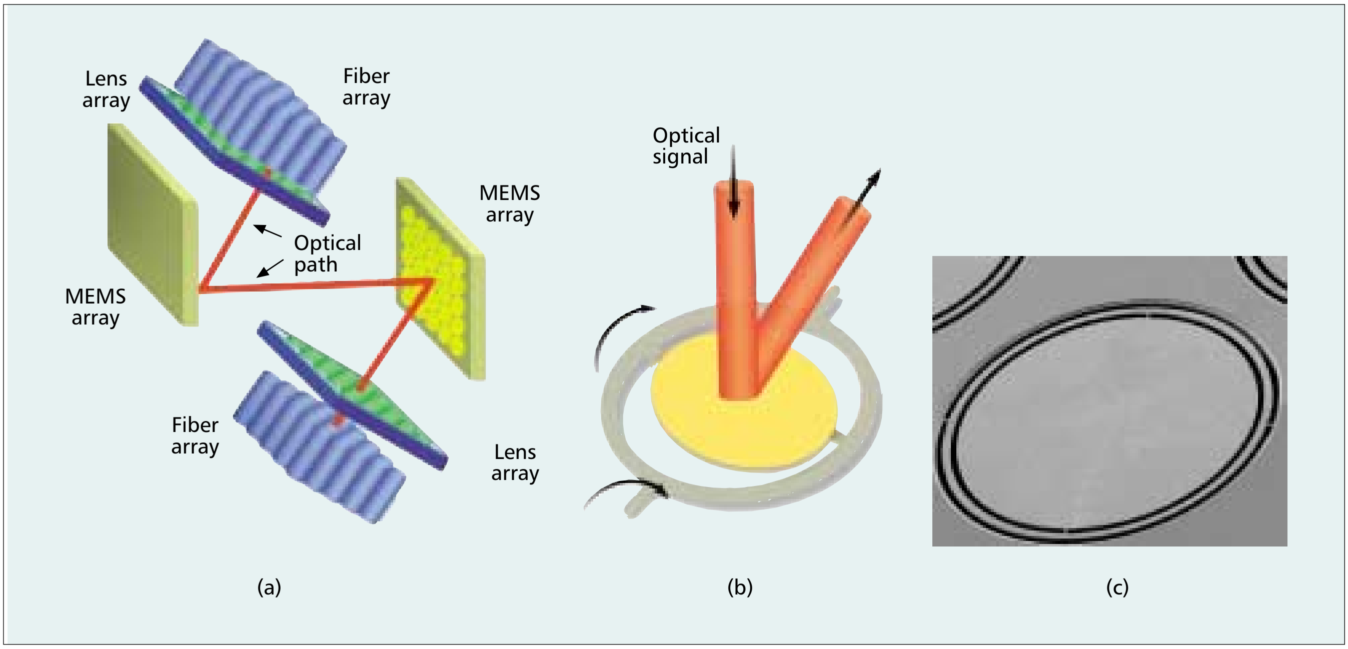


Figure 4. *a) Illustration of 3D switching architecture; b) illustration of beam steering using a two-axis gimbaled mirror; c) fabricated MEMS gimbaled mirror array.*

Three-Dimensional MEMS Switches — In the 2D case, all the light beams in the switch reside on the same plane, resulting in unacceptably high loss for large port counts. The second architecture (Fig. 4a), known as 3D switching [10–12], makes use of the three-dimensional space as an interconnection region, allowing scaling far beyond 32 ports with acceptable optical losses (< 10 dB). In this architecture, there is a dedicated movable mirror for each input and each output port. Each mirror must now operate in an analog, rather than binary, mode, tilting freely about two axes (Fig. 4b, c). This elegant architecture offers the virtue that the optical path length now scales only as $\sqrt{N}$ instead of N, so port counts of several thousand are achievable with losses below 10 dB. This 3D optical architecture clearly presents real hope for developing a scalable large-port-count OXC.

The Path to a MEMS-Based Optical Crossconnect

MEMS-based OXCs are no doubt feasible in concept. Substantial challenges must be overcome for any switch design; these challenges include MEMS mirror manufacturing, optomechanical packaging, and mirror control. Many aspects of these three challenges are interdependent. Complex trade-offs must be weighed in designing a MEMS-based OXC.

MEMS Design and Fabrication

Components of a large MEMS-based OXC include thousands of actuated mirrors, lenses, collimators, and fiber arrays. With no doubt MEMS mirrors, the key active element in the optical system, are the most critical technology for large OXCs.

MEMS Design — A two-axis actuated tilting mirror can be divided into three elements: the mirror, the springs as the mechanical support, and the actuator, all of which determine important OXC system parameters. Examples of these parameters include maximum port count (dependent on the mirror tilt angle), switch settling time (dependent on the mirror response time), insertion loss (dependent on the mirror size, reflectivity, and maximum tilt angle), and power dissipation (dependent on power required for mirror actuation and control). For a 1000-port switch, each mirror may require a diameter on the order of 1 mm, with mirror radius of curvature (ROC) greater than a few tens of centimeters. Reflectivity of each mirror is desired to be above 97 percent. The tilt angle requirement ranges from a few degrees to $\pm 10^\circ$ depending on the optical train design of the OXC.

The challenges in MEMS design come from the different trade-offs between desired properties of the MEMS device. As an example, the supporting springs for the mirrors must have sufficient stiffness to meet the mirror response time and vibration immunity requirement. But the upper bound of the spring stiffness is determined by the desired maximum tilt angle and the actuator's maximum force or torque output (as well as the switch power budget). Magnetic actuation and electrostatic actuation are two viable choices for mirror positioning. Magnetic actuation offers the benefit of large bidirectional (attractive and repulsive) linear force output but requires a complex fabrication process and electromagnetic shielding. Electrostatic actuation is the preferred method mainly because of the relative ease of fabrication and integration. However, to achieve large tilt angle using a stiff spring, the trade-offs include high actuation voltages (on the order of 50–200 V) and nonlinear torque output.

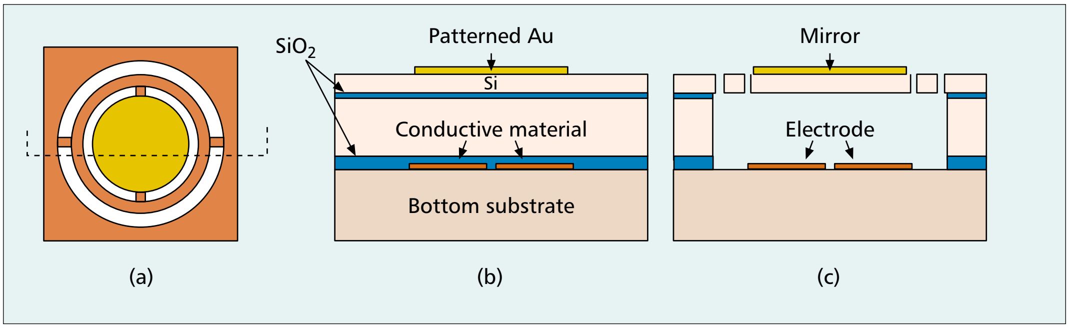


Figure 5. *a) Top view of a MEMS mirror; illustration of an SOI-based electrostatic MEMS mirror; b) before; and c) after structural release of the gimbaled mirror.*

A particular challenge for MEMS mirror design is to maximize ROC. A stable metal coating such as of gold, along with necessary additional metal adhesion and diffusion barrier layers, is often used as a reflective surface. These metal coatings can create an undesirable temperature-dependent mirror curvature due to intrinsic stress of the metal layers and the difference in thermal expansion coefficients of the metal coating layers and the bulk mirror made of a different material. This problem is especially severe if the metal coating is applied only to one side of the bulk mirror. A thick mirror can best counteract curvature from stress induced by metal coating on the mirror. Unfortunately, large mass leads to slow mirror response time and high sensitivity to stochastic vibration.

MEMS Fabrication Choices — In principle, the bulk mirror can be made of any material as long as reliability, reflectivity, and optical flatness requirements are met. Single-crystal silicon (SCS), commonly used in MEMS, is recognized to be the most suitable choice over polysilicon or electroplated metal due to low intrinsic stress and excellent surface smoothness. The choice of material for the mirror springs is arguably even more important because the mirror springs will constantly be twisted and bent. Superior mechanical characteristics make SCS the best candidate for the mirror springs. Alternative materials such as polysilicon and metal are poor substitutes because of potential stress, hysteresis, and fatigue problems. In most cases, the same material is chosen for both the bulk mirror and the springs in order to yield a straightforward fabrication process.

A plethora of fabrication processes can be used to create two-axis actuated SCS mirrors or mirror arrays [11, 13, 14]. Besides typical lithography, deposition, and etching procedures, necessary fabrication steps may include deep reactive ion etches (DRIE), silicon wafer bonding, and chemical mechanical polishing (CMP) [5]. Silicon-on-insulator (SOI) wafers are a convenient starting material to create SCS bulk mirrors with uniform thickness and low intrinsic stress (Fig. 5), but these wafers are unfortunately expensive with few supply vendors today. Applying clever silicon etching and wafer bonding techniques to cost-effective [100]-type silicon wafers may also yield mirrors with sufficiently low mass and large ROC. The primary differentiating factor between these MEMS mirror processes is device performance characterized by mirror size, flatness, reflectivity, maximum mirror tilt angle, and ease of mirror control. Material supply availability, length of fabrication cycles, and equipment bottlenecks play important roles in shortening product development cycle and time to market. Ease of circuit integration, achievable mirror array fill-factor, mirror array size, and manufacturing yield may also influence the overall switch fabric design. Arguably, a fabrication process that enables monolithic integration of electronics with MEMS [14] may lead to MEMS mirrors with the greatest functionality and the highest performance.

Optical Packaging

The optical system as shown in Fig. 4a requires thousands of micro-mirrors, lenses, and fibers aligned to each other with tolerances on the order of microns and hundreds of micro-radians. This multi-element body must endure thermal cycles, shock, and vibration during shipping and operation, which may lead to short-term and long-term mechanical drift in packaging. Obviously, tolerance of various pointing errors and misalignment errors depends on the robustness of the optical architecture design. In addition, these thousands of optical components must be carefully and compactly packaged with all the necessary control electronics in order to meet the additional space constraints and front panel accessibility requirements of telecommunications equipment.

For a typical Z-configuration 1000-port switch like Fig. 4b, coupling losses between the input and output fibers can be computed using Gaussian beam propagation methods. Component fabrication tolerances and packaging tolerances can also be estimated [4]. For example, ±1percent of focal variation in a single port lens in a lens array could account for up to 1 dB of optical loss. ±2 μm of relative position error in a fiber array can also lead to similar losses. One method to facilitate packaging is to make use of large fiber bundles, lenslet arrays, and monolithic dies with thousands of mirrors. The number of optical elements in the system may then be reduced to half a dozen or so. However, fabrication and packaging of such large fiber bundles, lenslet arrrays, and MEMS mirror dies poses formidable challenges of their own.

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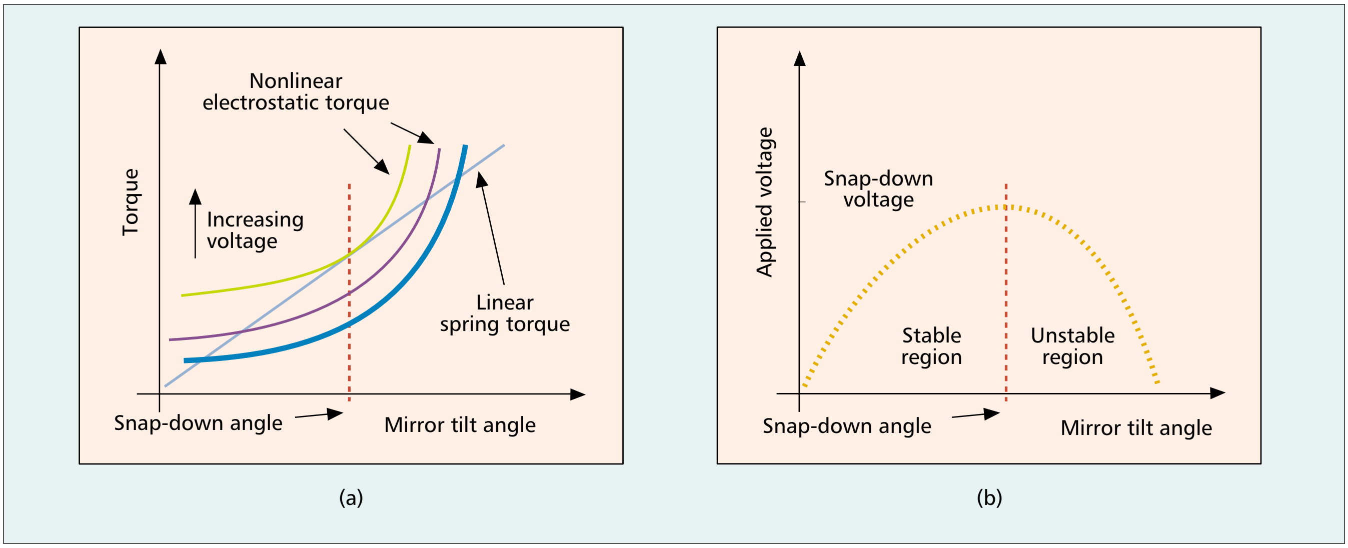

Figure 6. *a) For a given applied voltage, two intersection points are found between the nonlinear electrostatic torque curve and linear restoring spring torque curve, each corresponding to an equilibrium tilt angle; b) however, only the first intersection point is open-loop stable.*

Packaging of MEMS structures such as accelerometers and pressure sensors requires special attention beyond traditional integrated circuit packaging because of their sensitivity to contaminants, physical contact, and shocks. Packaging of optical MEMS structures on large (> 10 cm^2) dies introduces new complexities more challenging than ever before. To guarantee long-term operation of the MEMS mirror, the MEMS die should be hermetically sealed in a package with an anti-reflection (AR) coated optically clear window. Rigorous thermal management of the MEMS die package may be required since mirror ROC can be a strong function of temperature. Signal routing and inputs/outputs (I/Os) to the die are also paramount considerations. Due to the large number of die I/Os (1000 or more), a large die package with matching bonding pads and output pins is required. Fortunately, the latest land-grid array (LGA) and ball-grid array (BGA) with 0.5–1 mm pitch can easily meet the signal density requirements. Nevertheless, caution must be taken to minimize crosstalk and signal attenuation from routing inside the packages and through various connectors and cables.

A Control System for a MEMS-Based OXC

At the heart of a high-speed large capacity MEMS-based OXC is a robust mirror controller. The two main objectives of the controller are the following: first, guarantee that new port connections are successfully established within the allowed switching time; second, guarantee uninterrupted port connection after the new connections are established. In other words, upon request the controller must change the tilt angle of the MEMS mirrors quickly (within 5–10 ms after receiving the command) and then maintain the new position of the MEMS mirrors until a new connection request is received. A valid connection is characterized by achieving an insertion loss within 0.5 dB of optimum loss of the switch, which corresponds to a pointing error for each mirror of less than 100–200 μrad. This requirement alone poses a substantial challenge. Additional challenges come from the nonideal behavior of fabricated MEMS mirrors.

MEMS Mirrors with Nonideal Behavior — The MEMS mirror system to the first order can be characterized by the mirror mass, the mirror spring constant, and the damping coefficient. The mechanical behavior of the mirror (i.e., its response to sinusoidal excitations and step inputs) roughly matches that of a typical spring-mass system. In theory, a properly behaved mechanical system should be straightforward to design. Unfortunately, these three mechanical system parameters are not free variables that can be freely chosen. The mirror mass is governed by the mirror size and ROC (thus mirror thickness) requirement of the optical system. Likewise, the spring stiffness is bounded by the tilt angle range requirement, the available peak voltage (or current), and the maximum actuator force output. The damping factor also cannot be easily tuned by varying the mechanical designs.

In addition to the mechanical design constraints, ideal mechanical response may not be readily achievable depending on the choice of mirror actuation method. Consider the electrostatically actuated MEMS mirror in Fig. 5. This class of actuated mirror is among the simplest to fabricate. However, the system is inherently nonlinear and also unstable for large tilt angles (Fig. 6) [15]. The unstable open-loop region begins at the snap-down angle, which is independent of spring stiffness. When a voltage greater than the snap-down voltage is applied to the mirror, the mirror will swing to the most slanted position, hitting the substrate below the mirror. Using open-loop control, the MEMS mirror simply cannot rest at a tilt angles greater than or near the snap-down angle. Alternative electrostatic actuator designs based on comb-drive do not

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have an equally severe stability problem; however, a more complex fabrication process may be required [13].

To complicate matters further, MEMS devices may not be fabricated exactly as designed. Real devices will have fabrication imperfections and variations. During operation, the MEMS mirrors may also experience stochastic perturbation from the environment, including vibration from equipment cooling fans, heavy truck deliveries, door slams, earthquakes, etc.), and even interference from neighboring MEMS mirrors. Therefore, only an intelligent control system can guarantee timely and reliable port connections by the MEMS mirrors.

Open-Loop Control vs. Closed-Loop Control — Two control options are available: open-loop control and closed-loop control. Open-loop control can be straightforward to implement. A relationship between the mirror angle and the applied voltage must first be established by simulation or measurement. Then an appropriate voltage can be applied to the MEMS device to achieve a desired tilt angle. This control method requires minimal processing power, which is a definite benefit since the optical switch system must incorporate shelves of electronics to control 1000 or more MEMS mirrors. In addition, no mirror angle sensing hardware is needed. However, in such an open-loop system, a slight calibration error (due to simulation or measurement error or fabrication nonuniformity) or electronics drift will lead to steady-state error in the tilt angle for which there is no possibility of self-correction or compensation. In addition, an open-loop controller cannot adequately optimize settling time or overshoot characteristics. In terms of system stability and stochastic immunity, an open-loop controller in fact can offer no benefit. Therefore, open-loop control s not a robust solution.

From the system performance standpoint, the superior alternative to open-loop control is closed-loop feedback control. With feedback, it may be possible to extend the mirror tilting range beyond the snap-down angle. Using a feedback controller with a modest gain, the settling time, overshoot, and steady-state error can all be fine tuned according to system specification, even in the presence of mirror imperfection from nonideal MEMS fabrication. Most important, a MEMS mirror under feedback servo can be immune to random external shock and vibration. Potential performance benefits from feedback control are indeed overwhelming. However, an OXC with closed-loop controlled MEMS mirrors requires the development of a servo-control algorithm, the incorporation of sensing mechanisms for computing the proper control feedback signal, and the implementation of control electronics that offer sufficient computing power to control 1000 or more mirrors within the power and space budget of the switching fabric.

The All-Optical Horizon

Beyond the engineering challenges already described, deployment of all-optical MEMS-based OXCs as a network element still encounters additional hurdles. Network operators in general require switches with intelligence and functions such as performance-monitoring, connection verification, fault localization, bridging, keep-alive generation, and topology discovery [1]. Unlike all-optical switches, switches with competitive electronics-based technologies such as Tellium's Aurora Optical Switch can offer these functions at bit rates up to 10 Gb/s (OC-192). However, these technologies may not be optimal at higher bit rates, at or above 40 Gb/s (OC-768), in terms of cost, power, floor space, and complexity. On the other hand, transparent all-optical switch fabrics can uniquely offer raw aggregate capacity independent of bit rate. The best solution in the long run may be an optical-layer switch that encompasses a transparent optical fabric with the proper opto-electronic interfaces. Network architects thus carry the burden to exploit the benefits of these optical-layer switches.

Presently there are numerous commercial efforts developing MEMS-based all-optical switches. Well-known subsystem suppliers for MEMS-based switching include Analog Devices, Corning, Integrated MicroMachines, OMM, and ONIX. The latter two companies, OMM and ONIX, have recently announced focusing their technology development on 2D MEMS switching products instead of 3D MEMS products. Among many different factors, this change in development focus may be attributed to the more pressing need for smaller-size optical switches than large ones in the near term. Smaller less costly machines are expected to extend sales opportunity from the long haul to the metropolitan markets. In addition, smaller-port-count machines will support the concept of O-o-O and O-e-O machines at the same node of a network.

While many heated debates on network architectures still have not subsided, MEMS-based OXCs are slowly making the move from the laboratory to the network. However, the market for all-optical switches to date remains very limited. Limited deployment of small (256×256 or smaller) all-optical OXCs may take place as early as the first quarter of 2002. A sizeable market is expected to develop eventually in two to three years, likely followed by demand for larger-port-count (> 256) all-optical switches. While the surmounting engineering challenges for large OXCs seem numerous today, this market demand for large-port-count OXCs may be matched just in time by development efforts already underway.

Conclusion

MEMS technology offers the tantalizing possibility of advanced optical crossconnects with large port count, scalability, and switching capacity that can meet the switching demands in the ever faster, denser, rapidly growing WDM optical networks today and in the future. However, demonstration of field-tested and qualified large-port-count MEMS-based optical switches is still in the distant future. Exquisite engineering is necessary to overcome challenges in areas such as MEMS mirror fabrication, opto-mechanical packaging, and mirror control algorithm and implementation. While the available reliability data on MEMS devices from their brief history continue to improve, MEMS-based systems still must endure the test of time in order to establish trust and confidence in the telecommunications industry. Without a doubt, these engineering challenges as well as other marketing challenges will be overcome in due time. As MEMS technology continues to advance, one thing is clear: the powerful impact of MEMS as a disruptive technology for the telecommunications industry will never be forgotten.

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BIOGRAPHIES

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MEMS technology offers the tantalizing possibility of advanced optical cross-connects with large port-count, scalability, and switching capacity which can meet the switching demands in the ever faster, denser, rapidly growing WDM optical networks today and in the future.