1D MEMS-Based Wavelength Switching Subsystem

Steve Mechels, Lilac Muller, G. Dave Morley, and Doug Tillett, Network Photonics Inc.

ABSTRACT

Over the past few years, micro-electromechanical systems have emerged as a leading technology for realizing transparent optical switching subsystems. MEMS technology allows high-precision micromechanical components such as micromirrors to be mass produced at low cost. These components can be precisely controlled to provide reliable high-speed switching of optical beams in free space. Additionally, MEMS offers solutions that are scalable in both port (fiber) count and the ability to switch large numbers of wavelengths (> 100) per fiber. To date, most of this interest has focused on two-dimensional and three-dimensional MEMS optical crossconnect architectures. In this article we introduce a wavelength-selective switch based on one-dimensional MEMS technology and discuss its performance, reliability, and superior scaling properties. We also review several important applications for this technology in all-optical networks.

INTRODUCTION

Dense wavelength-division multiplexing (DWDM) is now widely used in transport networks around the world to carry multiple wavelengths on a single fiber. A typical DWDM transmission system may support up to 96 wavelengths, each with a data rate of up to 2.5 or 10 Gb/s. At present, these wavelengths usually undergo optical-electrical-optical (OEO) conversions at intermediate switching points along their end-to-end paths. In addition to being expensive, OEO conversions introduce bit rate and protocol dependencies that require equipment to be replaced each time the bit rate or protocol of a wavelength changes.

By switching wavelengths purely in the optical domain, all-optical switches obviate the need for costly OEO conversions, and provide bit rate and protocol independence [1]. This allows service providers to introduce new services and signal formats transparently without forklift upgrades of existing equipment. All-optical switching also promises to reduce operational costs, improve network utilization, enable rapid service provisioning, and improve protection and restoration capabilities.

As the capacity of DWDM transmission systems continues to advance, the most critical element in the widespread deployment of wavelength-routed all-optical networks is the development of efficient wavelength switching technologies and architectures.

Two main types of micro-electromechanical systems (MEMS) optical switches have been proposed and thoroughly covered in previous literature: 2D and 3D [2–4]. In this article, however, we focus on some of the unique advantages of 1D MEMS. These include integrated wavelength switching and scalability to high port count/high wavelength count switching subsystems.

2D MEMS SWITCHES

In a 2D MEMS switch, a two-dimensional array of micro-mirror switches is used to direct light from N input fibers to N output fibers (Fig. 1a). To establish a lightpath connection between an input and output fiber, the micro-mirror at the intersection of the input row and output column is activated (i.e., turned on) while the other mirrors in the input row and output column are deactivated (i.e., turned off).

One advantage of 2D MEMS is that the micromirror position is bistable (on or off), which makes them easy to control with digital logic.

Because the number of micro-mirrors increases with the square of the number of input/output ports, the size of 2D MEMS switches are limited to about 32×32 ports or 1024 micro-mirrors. The main limiting factors are chip size and the distance the light must travel through free space, which results in increased loss due to diffraction and loss variability across the input/output ports [2].

3D MEMS SWITCHES

3D MEMS switches are built using two arrays of N micro-mirrors. Each micro-mirror has two degrees of freedom, allowing light to be directed from an input port to any selected output port (Fig. 1b). Because the number of mirrors increases linearly with the number of input and output ports, 3D MEMS switches are scalable up

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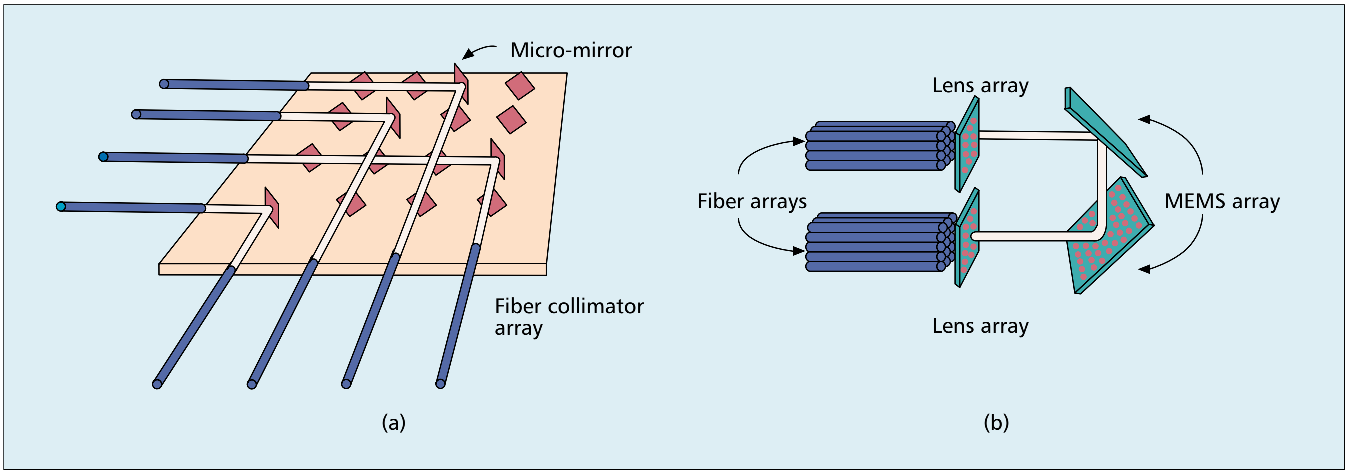


Figure 1. *Illustration of a) 2D MEMS; b) 3D MEMS optical switches.*

to thousands of input and output ports with very low insertion loss (~ 3 dB).

The design, manufacturing, and deployment of 3D MEMS switches, however, present some very significant challenges [3]. Complex closed-loop control systems are required to accurately align the optical beams. Because a separate control system is required for each micro-mirror, these solutions tend to be large, expensive, and consume lots of power.

Manufacturing yields have also been a problem for 3D MEMS technology. Typically, vendors need to build devices with more micro-mirrors than required to yield enough usable ones. Given the large number of switching combinations, testing and calibration of these switches can take days to complete. There is also the issue of fiber management. Depending on the size of the switch, anywhere from a few hundred to a few thousand individual fibers are needed to interconnect the switch with other equipment. This also applies to 2D MEMS switches because in both cases a single fiber connection is required per wavelength.

1D MEMS-BASED WAVELENGTH-SELECTIVE SWITCH

Both 2D and 3D MEMS are port (fiber) switches. To switch wavelengths on a DWDM signal, the incoming light must first be completely demultiplexed. In contrast, a 1D MEMS-based wavelength-selective switch (WSS) integrates optical switching with DWDM demultiplexing and multiplexing. This alleviates the fiber management problem, and results in a device with excellent performance and reliability. An illustration of a 1D MEMS-based WSS is shown in Fig. 2a. Light leaves the fiber array and is collimated by a lens assembly. A dispersive element is used to separate the input DWDM signal into its constituent wavelengths. Each wavelength strikes an individual gold-coated MEMS micro-mirror (Fig. 2b), which directs it to the desired output fiber where it is combined with other wavelengths via the dispersive element. Each individual MEMS mirror has a surface area of approximately 0.005 mm^2. Because the spot size of the lens is small compared to the MEMS mirrors, the optical bandpass properties of the switch are outstanding.

When integrated with a dispersive element, the 1D MEMS array requires only one micro-mirror per wavelength. Therefore, the switch scales linearly with the number of DWDM channels. In addition, the switch can be controlled with simple electronics in an open-loop configuration because each micro-mirror has two stable switching positions. This results in a dramatic reduction in size, cost, and power consumption compared to other MEMS switching technologies.

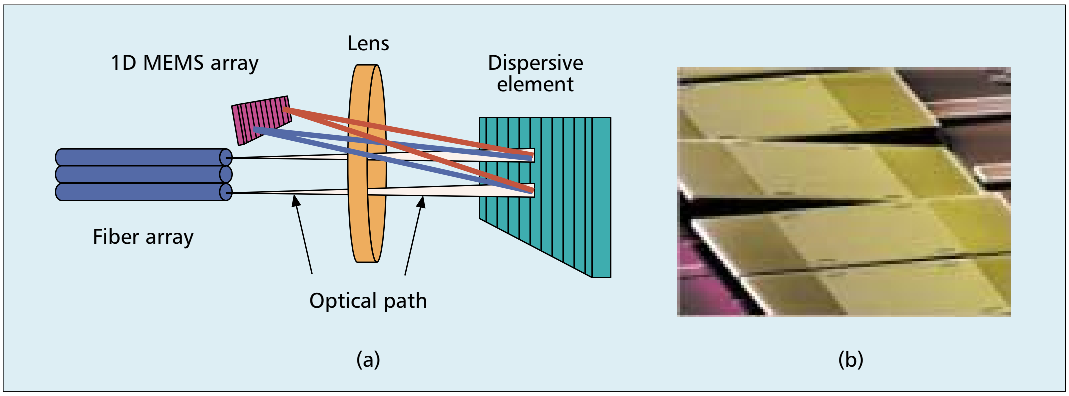
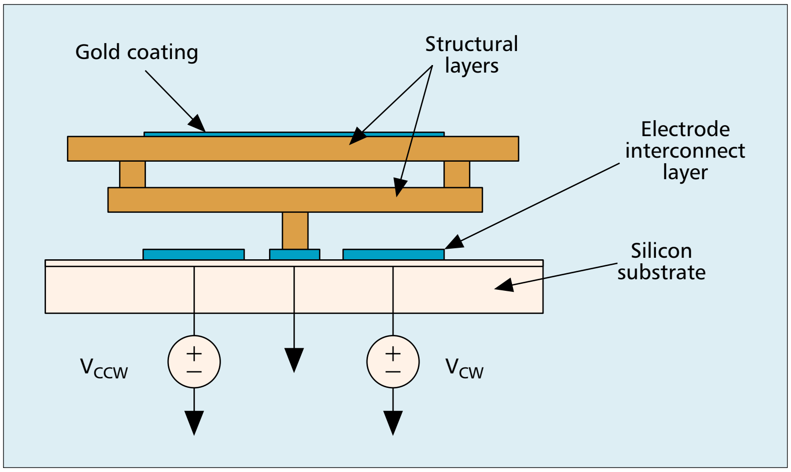
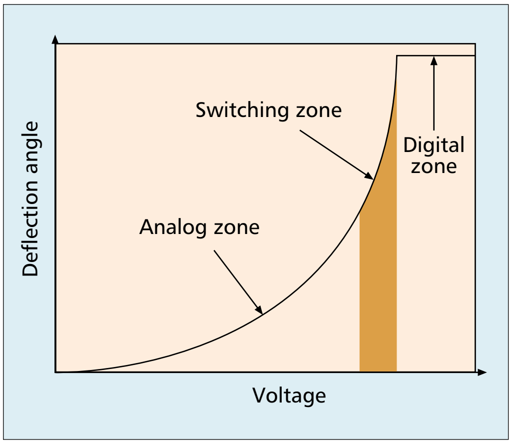


Figure 2. *a) Illustration of 1D MEMS wavelength-selective switch; b) 1D MEMS micro-mirror array.*



■ **Figure 3.** *Illustration of a micro-mirror fabricated using surface micromachining.*



■ **Figure 4.** *Micromirror characteristic response. The switched position of the1D micro-mirror is in the highly stable digital zone of the curve.*

1D MEMS FABRICATION

In the MEMS field, the two leading technologies are surface and bulk micromachining. Until now, surface micromachining has been perceived to be at a disadvantage primarily due to higher curvature and other surface deformations of the structural layer for large (≥ 1 mm^2) micro-mirrors [5]. However, 1D MEMS requires much smaller MEMS mirrors than 2D or 3D MEMS. In addition, significant technological process and design breakthroughs in surface micromachining have further mitigated these concerns. As a result of these changes, the advantages of bulk micromachining have been eclipsed. Figure 3 shows a cross-section of a micro-mirror fabricated using a surface micromachining process.

Surface micromachining has several advantages over bulk: it affords numerous structural layers that provide significant design flexibility (e.g., flexures buried underneath the mirror structure allow for reduced mirror-to-mirror gaps) over typical single-layer bulk technology [6]. Additionally, surface micromachining uses standard semiconductor processes and tools. Consequently, the complementary metal oxide semiconductor (CMOS) approach to standardization of the MEMS fabrication process for several industries (e.g., optical and RF) is possible. The CMOS model offers tremendous yield, quality, manufacturability, availability, and reliability advantages.

MIRROR CONTROL

1D MEMS mirrors are tilted at a small angle (< 10°) using open loop control. The force to tilt a mirror is generated by electrostatic force. The electrostatic attraction between the mirror and electrode consumes essentially no power (there is no current draw), but effectively deflects the mirror toward the electrode and holds the mirror down against a mechanical stop. Figure 4 shows mirror position as a function of applied voltage.

Tilting the mirror to the other position is a simple process of removing the charge from one electrode and charging the opposing electrode, thus tilting the mirror in the opposite direction. The simplicity of the electronics is a result of no in situ sensing or closed loop control. The electronics hardware uses off-the-shelf components that have proven reliability in other applications.

OPTICAL PERFORMANCE

The optical performance characteristics of an all-optical switching platform are a key consideration in transparent optical networks. Some of the more important parameters are insertion loss, channel passband shape, switching time, PDL, and port isolation. Insertion loss is a critical parameter because it has a direct impact on system performance and cost.

Figure 5 shows the insertion loss for 5 of 96 operating channels in a 1D MEMS WSS. Insertion loss uniformity is within ±0.5 dB across all channels. Both 2D/3D MEMS solutions require external demultiplexers/multiplexers to switch wavelengths; the loss of a typical demultiplexer varies from 3 to 9 dB. Therefore, the loss of the WSS is exceptionally low when one considers that it includes switching with the demultiplexing and multiplexing functions. Lower loss translates into fewer amplifiers, higher optical signal-to-noise ratio (OSNR), and/or greater system reach. Figure 5 also provides a detailed plot of the channel passband shape for 50 GHz channel spacing. The wide, flat channel passband is particularly important in systems where many devices are cascaded because it prevents passband narrowing.

The device also exhibits excellent port-to-port isolation and adjacent channel crosstalk (both > 40 dB). The high port isolation offered by MEMS is critical because coherent crosstalk can be a potentially serious impairment when wavelengths are being reused in an optical system. Given the small size of the micro-mirrors, the switching times are also extremely fast (< 250 μs). This is especially important in protection switching applications, where connections must be restored in less than 50 ms to prevent service layer connections from dropping out.

RELIABILITY

Another critical requirement for all-optical switching technology is high reliability. Stringent reliability standards have already been developed for all-optical switching systems, and switch packages must conform with these standards, including Telcordia 1209, 1221, 1073, and GR-63 for subsystems.

The 1D MEMS is the only moving component in a WSS switch and is therefore the primary focus for reliability investigations. The reliability of electrical, mechanical, and optical components was also addressed throughout design and fabrication. Silicon is the primary working material; it has a yield strength that ranges from four to eight times that of steel. Silicon is a purely elastic material: it shows no "memory" phenomena (i.e., hysteresis), no creep at low temperatures (< 800°C), no fatigue up to 10^9 cycles, and very high fracture strength. The 1D MEMS approach allowed the use of standard integrated circuit (IC) fabrication processes and equipment in a Class 1 Cleanroom. IC-based fabrication technology very precisely forms and aligns silicon structures. These are the same fabrication techniques and tools used to manufacture several fully qualified, highly reliable products such as airbag accelerometers.

It has been demonstrated that the micro-mirrors can be exercised, or cycled, over 1 million times without any mechanical degradation. This ensures mirror position accuracy over the lifetime of the switch.

The primary reliability concern in 1D MEMS-based WSS is adhesion between the mirror and the hard stop, particularly after a long-term dormancy period. This phenomenon, often referred to as *stiction*, can be controlled with proper design of the micro-mirror device and package. Proper control of ambient conditions within the enclosure also significantly reduces the risk of long-term stiction; therefore, the 1D MEMS array is housed in a hermetic low-moisture inert environment.

Over 1 million test hours utilizing accelerated aging environments have been performed to validate the design and processes. Table 1 summarizes test results to date to evaluate MEMS failure modes under highly accelerated test conditions.

1D MEMS-based WSS offers another advantage over 2D and 3D MEMS approaches by significantly reducing the mirror packing density of the die. While 2D or 3D MEMS typically occupy much of the surface area on a large silicon die, small 1D MEMS can be arranged in a linear configuration that occupies only a small fraction (< 1 percent) of the die. This results in higher manufacturing yields due to lower susceptibility to contamination and handling damage, and allows the die layout to be driven by packaging needs, thereby increasing the yield and reliability of the overall packaged device.

In summary, the 1D MEMS design is extremely robust in all critical environments including temperature, moisture, vibration, shock, and cycling.

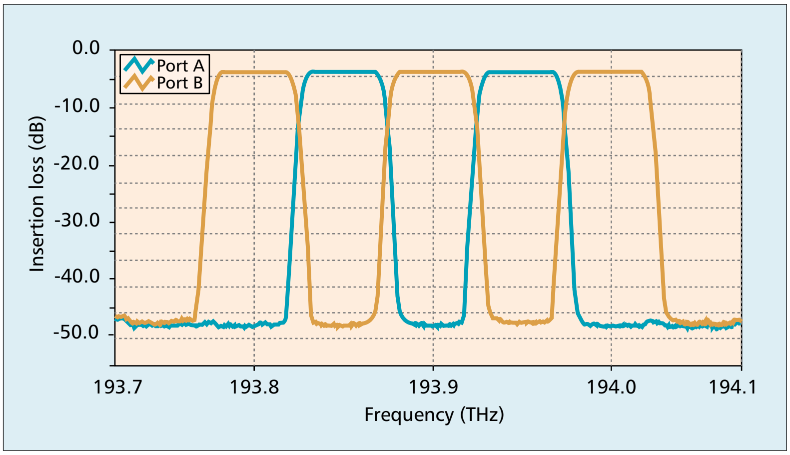


Figure 5. *Insertion loss of a1D MEMS wavelength selective switch with alternate channels routed to ports A and B. The plot shows a close-up view of insertion loss for five channels spaced at 50 GHz intervals.*

Accelerated Life Tests	Results
Durability: over 1,000,000 cycles	No failures
Voltage: 1.6× normal – 2400 h	No failures
Moisture: 15× normal – 2400 h	No failures
Operating temp.: –10°C to +105°C	No failures
Reliability: 29 units 45°C, 65°C, 85°C, 1.5× normal voltage, 10,000 h	No failures

Table 1. *MEMS accelerated Life Tests.*

APPLICATIONS: 1D MEMS WAVELENGTH SELECTIVE SWITCHES

The wide spectral passbands and excellent optical properties of 1D MEMS open up a wide variety of applications for the technology. Three significant applications for 1D MEMS WSS are reconfigurable optical add/drop multiplexers (ROADMs), wavelength crossconnects, and hybrid WXC/OEO grooming switches. These are discussed below. Other applications include protection switching and dual ring interconnect.

RECONFIGURABLE OADM

ROADMs enable optical wavelengths to be dynamically added/dropped without the need for OEO conversion. ROADMs are beginning to replace fixed wavelength OADMs, because they are flexible, and therefore able to deal efficiently with network churn and dynamic provisioning scenarios. As "all-optical" distances increase in fiber systems there are fewer mid-span OEO sites. Previously these OEO sites were natural locations for add/drop, but now they are being replaced by inexpensive ROADMS. As with all elements in an all-optical path, ROADMS must be cascadable with minimal signal degradation on express traffic.

While the required add/drop functionality can be partially addressed with a variety of solutions, including band switching and partial wavelength reconfigurability, these solutions do not support 100 percent add/drop capability and are not cost effective as DWDM channel counts increase. Ideally, service providers would prefer to deploy a flexible add/drop network element to effectively address low initial cost requirements, low operating expenses, required flexibility, and scalability to handle changing and unpredictable traffic demands.

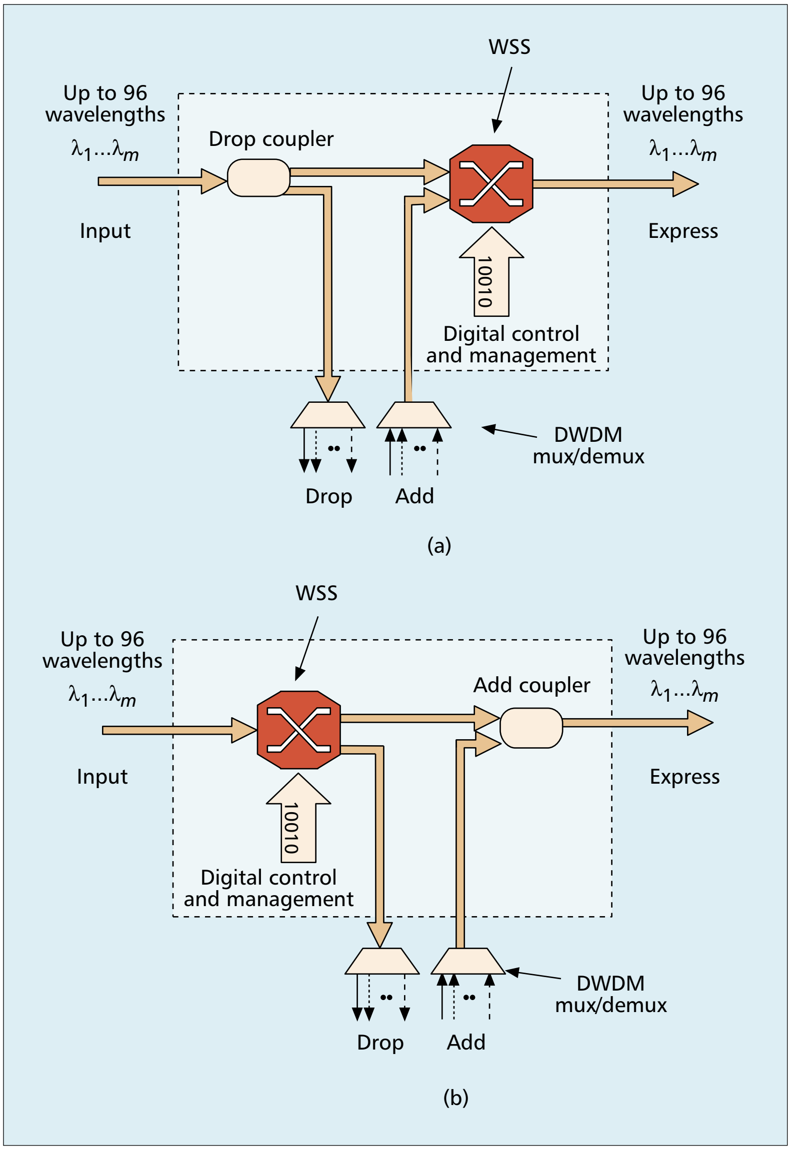


Figure 6. *ROADM architectures: a) broadcast and select; b) preselect.*

Wavelength selective switches, based on 1D MEMS technology, allow one to individually address any wavelength and thus enable 100 percent add/drop. Wavelengths can be reassigned from the express path to the add/drop paths with no effect on the remaining express traffic.

A number of architectural approaches can be adopted for wavelength-selective switch (WSS) based ROADMs. For example, in Fig. 6a a broadcast and select ROADM architecture is shown. In this configuration, DWDM traffic enters the ROADM and a drop coupler provides access to all incoming traffic. Add traffic enters via the 1D MEMS-based switch, which allows one to select wavelengths from either the input/express path or the add path. Final demultiplexing must be accomplished with the use of grid-compliant filters.

Alternatively, a preselect drop architecture may be adopted (Fig. 6b). In this configuration, input traffic enters the WSS, now utilized in a 1×2 configuration. Wavelengths are routed to either the express or drop port. Add traffic joins the express traffic through a coupler.

The bidirectional MEMS switch allows for both configurations. Any combination of wavelengths can be expressed or dropped in both of the ROADM architectures. A WSS will also act to filter ASE noise on unused frequencies in both of these configurations.

WAVELELENGTH CROSSCONNECT

Two conventional approaches to providing wavelength switching using 2D and 3D MEMS switches are shown in Fig. 7. The architecture shown in Fig. 7a is best suited to 3D MEMS switches and is sometimes referred to as a *wavelength interchanging crossconnect* (WIXC) [7, 8]. One advantage of the WIXC architecture is that it supports wavelength conversion, regeneration, and performance monitoring for all wavelengths. These capabilities come at a significant cost, however, because each wavelength handled by the switch requires a bidirectional transponder. In addition to being expensive, transponders are typically bit rate and protocol dependent. Therefore, any changes in signal type or format may require costly equipment upgrades.

The second approach is shown in Fig. 7b. This architecture is known as a *wavelength-selective crossconnect* (WSXC) [4] and is more suitable for 2D MEMS switches. It consists of n DWDM demultiplexers, m wavelength-independent $n \times n$ space switches, and n DWDM multiplexers. The DWDM demultiplexers in the first stage are used to route individual incoming wavelengths onto separate fibers. For each wavelength, a separate $n \times n$ space switch is used to route each of the n input signals to the appropriate output port, where the signals are combined via a DWDM multiplexer.

A key advantage of this three-stage architecture is that bidirectional transponders are not strictly required for each wavelength. This significantly lowers the average cost per wavelength compared to the WIXC architecture. The switching core is also much less complicated than the WIXC architecture because it contains many small switch matrices (e.g., 4×4) rather than one large complex switch matrix. The WSXC architecture is also bit rate and protocol independent, provided that all-optical switching is used to implement the $n \times n$ space switches shown in Fig. 7b. A drawback of this architecture is that the number of $n \times n$ switches required scales 1:1 with the number of DWDM wavelengths in the system.

Implementing a WSXC or WIXC using discrete components also has several other drawbacks. These include size, cost, insertion loss, passband characteristics, scalability, control complexity, and fiber management. Another drawback of a three-stage implementation using 2D MEMS switches is that it cannot be upgraded incrementally from low fiber counts to high fiber counts without replacing the existing switch matrices.

Several WSXC architectures can also be implemented using 1D MEMS-based WSSs. A particularly efficient one is the *broadcast and select* architecture shown in Fig. 8.

This architecture is functionally equivalent to the three-stage implementation shown in Fig. 7b but provides several advantages. The most striking is the difference in the number of devices. For example, the 4 × 4 WSS-based design described above requires only four devices, whereas the 2D MEMS design requires one switch matrix per wavelength (e.g., 96 switch matrices for a 96-channel WSXC). In general, this difference translates into smaller physical sizes, lower cost, less power, and higher reliability for the 1D MEMS-based solution.

An obvious advantage is a marked reduction in the number of fiber connections. For example, the three-stage implementation of a 4 × 4 WSXC requires over 700 fiber connections, whereas the broadcast and select architecture using a WSS requires only 24, as shown in Fig. 8. This fiber reduction improves system reliability and eliminates the fiber management headache associated with a three-stage implementation. In fact, a 1D MEMS 4 × 4 WSXC system with 3.36 Tb/s of aggregate switching capacity has been demonstrated in less than half a rack.

Unlike the 2D MEMS solution, the broadcast and select architecture can also scale incrementally from low to high port (fiber) counts without a forklift upgrade. This is accomplished by adding extra WSS switches and couplers to the existing switch fabric. With $1{:}N$ equipment protection, this upgrade can be performed while the WSXC is in service. Procedures for upgrading the broadcast and select architecture from a 2 × 2 WSXC to an 8 × 8 WSXC have been developed. It is even possible to upgrade from a reconfigurable OADM to an $N \times N$ WSXC while in service.

HYBRID OPTICAL CROSSCONNECT

OEO switches have been deployed extensibly at long-haul junctions to switch wavelengths and perform additional functions such as wavelength conversion, regeneration, and subwavelength grooming. In a hybrid optical crossconnect, the switching is done in the cost-effective WSXC system, while the other functions are left to the OEO switch as shown in Fig. 9 [9–12].

A conservative analysis of this *hybrid optical crossconnect architecture* shows that, for an 8 × 8 crossconnect with 30 percent add/drop traffic and 80 percent system fill, roughly 60 percent fewer transponders and 50 percent fewer switch ports are required compared to the equivalent WIXC configuration [13]. This translates directly into substantial cost savings, even when the cost of an individual wavelength-switching element is equal to a transponder (it is typically less).

CONCLUSION

In the current telecom environment of restricted capital budgets and ever increasing demand, carriers need wavelength switching architectures that can scale economically from small to large port counts without forklift upgrades of existing equipment. 1D MEMS-based wavelength switching platforms offer highly scalable solutions with excellent optical properties. Additionally, the simple digital control and fabrication of linear MEMS arrays offer all the benefits of all-optical networking without the risk, high costs, and complexity associated with larger dimensional 2D and 3D MEMS-based approaches.

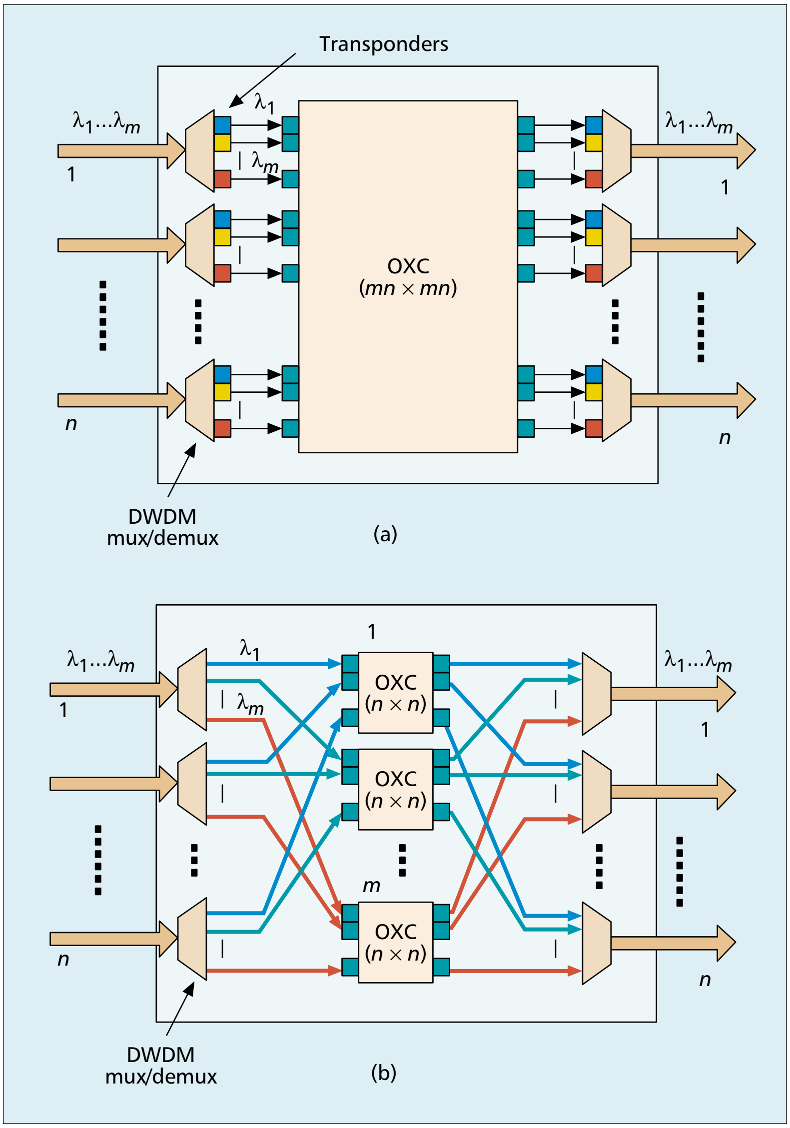


Figure 7. *Illustration of a) wavelength interchange crossconnect; b) wavelength-selective crossconnect architectures.*

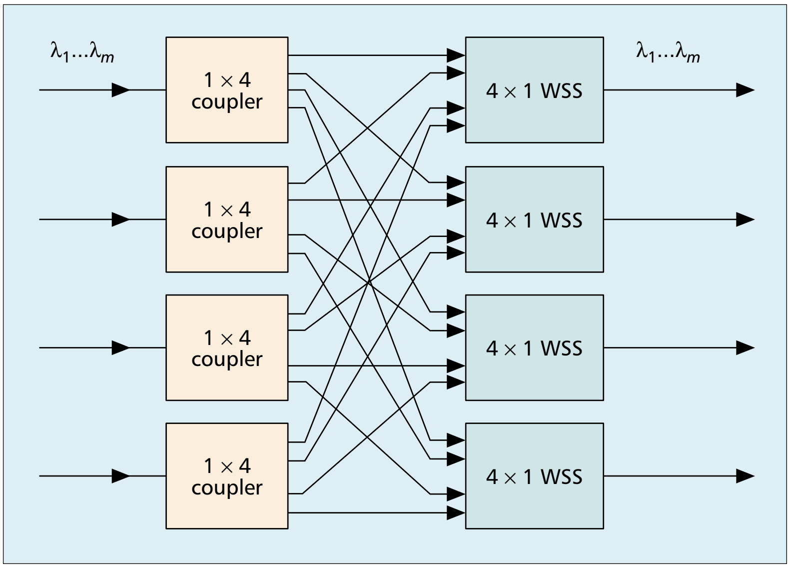


Figure 8. *An illustration of a 4 × 4 broadcast and select wavelength-selective crossconnect.*

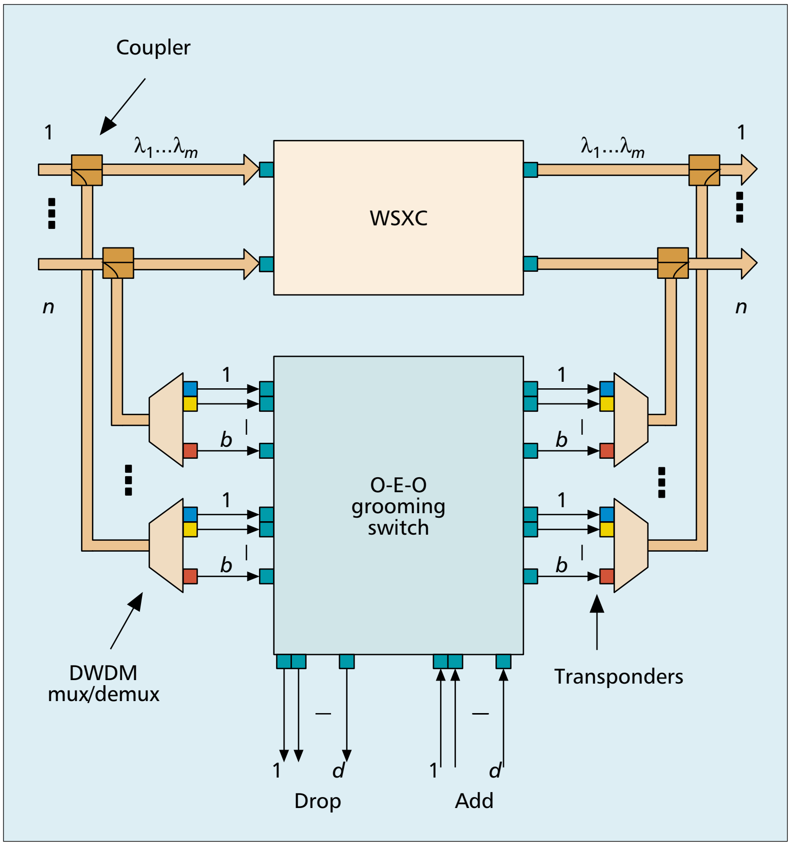


Figure 9. *Hybrid optical crossconnect.*

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BIOGRAPHIES

STEVE MECHELS (steve.mechels@networkphotonics.com) currently leads the technical marketing group at Network Photonics, Inc. Since joining Network Photonics in 2000, he has also worked on the design and simulation of DWDM metro systems. Prior to joining Network Photonics, he was a senior member of technical staff at Tyco Submarine Systems, where he evaluated optical components and worked on ultra-long-haul fiber optic testbeds. During graduate school he worked as an opto-electronic engineer at the National Institute of Standards and Technology, where he won the U.S. Department of Commerce Gold Medal in 1994 for work involving fiber geometry standards. He also worked as a guest researcher for one year at NTT Laboratories in Ibaraki, Japan, studying arrayed waveguide gratings and developing optical low-coherence reflectometry measurement systems. He holds a Ph.D. in electrical engineering from the University of Colorado at Boulder.

LILAC MULLER is currently the technical group lead for MEMS development at Network Photonics, Inc. She earned a Ph.D. in mechanical engineering from the University of California at Berkeley in May 2000. Her research at Berkeley focused on developing and utilizing high-aspect-ratio microfabrication technologies for mechanically robust applications, such as hard disk drives. She received Bachelor's and Master's degrees from the Department of Aeronautics and Astronautics at MIT in 1993 and 1994, respectively. After leaving MIT, she worked at NASA's Jet Propulsion Laboratory (JPL) developing microspacecraft concepts and microtechnologies for deep space applications.

G. DAVE MORLEY is a senior optical network engineer with Network Photonics, Inc. Since joining Network Photonics 2001, he has worked on the software architecture for a DWDM ring planning tool, fault monitoring and protection schemes, and wavelength crossconnect architectures. Prior to joining Network Photonics, he was a senior consultant with VPIsystems Inc. Between 1996 and 2000, he worked as a research engineer at TRLabs developing state-of-the-art optimization algorithms for ring-based network design. He holds a Ph.D. in electrical engineering and an M.B.A., both from the University of Alberta, and is a Professional Engineer in the Province of Alberta.

DOUG TILLETT is the director of reliability and product assurance at Network Photonics. He is responsible for reliability and qualification testing of one of the Telecommunications industry's first generally available all optical switch deploying MEMS technology. Previously, as quality and reliability manager at CISCO Systems, he implemented an extensive analysis and test program to achieve 7-9's availability on the Wavelength Router™ System. He also worked at Texas Instruments where he led the reliability and quality effort to transition a MEMS technology, digital micromirror device or DMD™, from research and development to production. He holds a B.S. degree in electrical engineering from Virginia Polytechnic Institute and State University.