The emergence of all-optical communications is being enabled in large part by new technologies that free networks from the data rate, bandwidth, latencies, signal loss, cost and protocol dependencies inherent in optical networks with electrical conversion. Along with eliminating many of the limitations of optical-electro-optical (OEO) networks, the newer technologies—dominated in large part by microelectromechanical systems (MEMS)-based micromirrors—have one more trick up their sleeve. By allowing external control of the optical switching outside of the optical path, the electronics and optical parameters can be adjusted independently for optimal overall results.

Before the advantages of a MEMS-based, all-optical (OOO) network can be realized, however, the designer must weigh the pros and cons of the two-dimensional—or three-dimensional—MEMS options while carefully evaluating how such issues as control loops, testing and packaging have been addressed. Fortunately, newer, more responsive and accurate control loops have been devised that greatly enhance the viability of MEMS devices. In addition, hermetically sealed, glass-lidded packages have arisen to give the devices a large degree of standardization and immunity to the moisture and environmental concerns that have slowed their penetration. Fully tested and qualified, the devices go a long way toward decreasing the time-to-market of optical MEMS while increasing reliability and performance.

**OEO-based networks**

Currently, optical-communications networks are dominated by systems that convert optical signals into electrical signals for switching, routing, etc., before converting the signals back into the optical domain. Often, maintaining these signals in the optical domain provides the greatest efficiencies. Until recently, however, the optical signals could only be handled as electrical signals.

Unfortunately, in OEO networks conversion has significant limitations and drawbacks. OEO systems must be compatible with the data rate, bandwidth and protocol of the signals, and multiple conversions add latency and cost to the system. In addition, dense wavelength-division-multiplexed (DWDM) systems must break up the light into its multiple-wavelength components in order to process the signal.

Despite those drawbacks, however, communications networks based on OEO systems have taken a lead in optical networking, in large part because the components necessary to implement these systems are readily available. Additional benefits include the ability to groom and regenerate signals. The need

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**FIGURE 1:** 3D MEMS (b) substantially reduces the number of mirrors required vs. 2D MEMS (a).

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to be compatible with data rates, protocols and wavelengths, however, presents a considerable drawback because carriers must make substantial investments to upgrade their networks as those parameters change over time.

**OOO-based networks**

Transparent, all-optical networks remedy the drawbacks of OEO systems by preserving signals in the optical domain. An OOO physical-switch fabric based on highly reflective mirrors allows optical signals to be manipulated with minimal signal loss without converting the signal. The lack of signal conversion means that an OOO system can be independent of data rate, bandwidth, protocol or even DWDM composition.

Another difference between OEO and OOO systems is the position of the electronic controls with respect to the optical signals. In the OEO system, the electronic controls and the converted optical signal are one and the same. This requires system implementers to make trade-offs between the electronics and the optics. In the OOO system, electronics control the optical switch outside the optical signal path. This enables system implementers to optimize electronics and optics independently to achieve the best results.

The primary challenge in building all-optical systems is the availability of high-performance, reliable and cost-effective components that can be readily implemented. MEMS have emerged to enable many of these components. Their fabrication is similar to standard semiconductor integrated-circuit processing and in many cases, MEMS products are fabricated on the same manufacturing line as ICs. This allows them to leverage the quality, reliability and cost efficiency of standard IC products.

In an all-optical system, there are two ways to switch optical signals: transmissive and reflective. In the transmissive method, a signal normally passes through to a given output unless interrupted and redirected to a different output. Reflective methods make use of highly reflective surfaces to steer optical signals.

In the realm of reflective technologies, there are two primary MEMS-based architectures: 2-D and 3-D MEMS. Two-dimensional MEMS have taken an early lead in the adoption of optical MEMS components, but they are not readily scalable, and they pose additional drawbacks. It is generally acknowledged that 3-D MEMS will become the predominant technology for optical MEMS.

Two-dimensional MEMS devices use reflective micromirrors to redirect optical signals within a fixed plane, as shown in Fig. 1a. With 2-D devices, mirrors flip up into a set position to reflect light from one fixed port to another. Switching to a different port requires that a different mirror be set into position. From the figure, it can be seen that for N ports, \( N^2 \) mirrors are required. This makes implementations beyond 32, or even 16, complex and inefficient (e.g., a 32-port switch requires 1,024 mirrors, of which only 32 are ever in use at any given time). Additionally, the optical path length, and therefore the optical loss, depends on which ports are involved. This complicates the optical design and, in some cases, requires optical signal conditioning to balance out the signal strength of all the signals.

3-D MEMS devices utilize mirrors gimbaled along two axes to rotate the mirrors and steer the optical signal out of a fixed plane and into free space. Three-dimensional architectures typically employ two arrays of mirrors, each aligned to an array of collimated input or output fibers. This requires the use of 2\( N \) mirrors for \( N \) ports, considerably less than 2-D architectures. Fig. 1b shows an example of an implementation of a 3-D optical MEMS switch that employs an intermediary reflective surface to fold and shorten the optical path.

Actuation of the mirror is typically through the use of electrostatics, where electrodes underneath the mirror form a capacitor with the mirror itself (see Fig. 2). Applying a voltage to the electrodes generates an electrostatic force that pulls the mirror toward the electrode. As the mirror tilts closer to the electrode, the force becomes stronger and less voltage is required to tilt the mirror until the mirror touches down to the silicon surface.

**3-D MEMS advantages**

3-D optical MEMS possess numerous advantages over 2-D MEMS as well as over OEO-based switches. The free-space nature of 3-D MEMS provides path-independent loss that ensures that signal strength is inherently balanced, and 3-D MEMS arrays are readily scalable from 2 x 2 switches up to and beyond 1,024 x 1,024 switches. Control over the tilt of the mirrors allows for dynamic alignment of the mirror to the fiber, reducing assembly costs as well as enabling variable optical amplifier functionality. Two-dimensional MEMS mirrors behave in a digital manner and lack the analog tilting precision of 3-D MEMS mirrors. In short, 3-D MEMS are
ideal for large and small port counts for switches and other optical components.

In order to take full advantage of the benefits of 3-D optical MEMS, however, it is necessary to provide a responsive closed-loop servo control to position the mirrors accurately. The difficulty in doing that has, in part, impeded the adoption of 3-D optical MEMS. In traditional 3-D MEMS technologies, position control requires optical feedback that is not capable of correcting for shocks, vibrations and other short-term instabilities and changes.

**Integrated electronics**

A new 3-D MEMS technology is emerging that employs integrated position-sense electronics that can be used in a closed-loop control scheme to position mirrors and maintain stability. The 3-D MEMS mirror in Fig. 2 shows the position-sensing electrodes located along the outer perimeter of the actuation electrodes. Fig. 3 shows the output of the integrated position-sense circuitry. The integrated electronics determine position by measuring capacitance changes between the mirror and the sense electrodes. On-chip electronics can also be designed to condition the position signal to reduce noise, thereby providing accurate position information.

Integrated electronics also reduce the interconnect burden by allowing signals to be multiplexed on-chip. If each mirror has nine terminals (four actuation electrodes, four sense electrodes and one mirror), then a 3-D MEMS array with N mirrors would require at least 9N connections to control the mirrors. For a 64-mirror array, that translates to more than 576 connections. Integrated electronics that multiplex those 9N signals could reduce the I/O count to less than 40 connections. This drastic reduction in I/O reduces interconnection costs and increases overall system reliability.

**Packaging improvements**

Today, suppliers are beginning to provide MEMS in standard packages that are hermetically sealed with a glass lid. The products come fully tested and qualified and ready for system implementation. This trend dramatically reduces development expenses and time-to-market while increasing reliability and performance.

As these devices are deployed, advances are continually occurring on the process side to enhance the performance of optical MEMS. As an example, the Optical iMEMS process from a well-known vendor allows the development of a 3-D optical MEMS component with an array of 64 mirrors suitable for use in 64-, 128-, 256- and 512-port configurations for optical switching, attenuation and tuning and alignment. This technology utilizes a silicon-on-insulator construction, BiCMOS high-voltage electronics and gold metallization.

The general-purpose array of 64 mirrors is diagramed in Fig. 4 and uses mirrors similar to those shown in Fig. 2. The mirrors can rotate ±6° in each axis, while on-board electronics with low-noise capacitive sensing detect mirror tilt position. Key specifications for a 64-mirror array are given in Fig. 5.

The device is hermetically sealed but has a glass window for access. The integration of electronics and mirrors reduces I/O count, while the hermetic sealing eliminates the need for additional MEMS component assembly.

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