OPTICAL SWITCHING

The Lucent LambdaRouter: MEMS Technology of the Future Here Today

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ABSTRACT

MEMS devices are beginning to impact almost every area of science and technology. In fields as disparate as wireless communications, automotive design, entertainment, and lightwave systems MEMS is increasingly becoming a key technology. In this article we discuss MEMS devices in general, show how and where they will be used in lightwave systems, and then show in detail how they are allowing a billion dollar business to be born, that of large all-optical crossconnects. In particular we will highlight one particular device, the Lucent LambdaRouter, and show how it is built from the chip on up and discuss its performance and applications.

INTRODUCTION

Despite the recent slowdown in the telecom equipment market, the underlying fundamentals of our industry remain strong. The demand for bandwidth, the driver for everything we do, is still growing at a compound annual growth rate (CAGR) of 100 percent. This then drives the need for ultra long-haul transmission systems, optical crossconnects at the nodes, metro rings to feed these core networks, and access networks to drive bandwidth into all of the above. All of this will be done under the control of MPLS signaling protocols. In this article we focus on the role of the large optical crossconnect for core switching and show how MEMS is the only technology currently capable of allowing high-capacity scalable architectures.

The need for crossconnects in core networks is driven by the desire of service providers to offer a rich new class of wavelength services. Designing networks around wavelengths instead of packets allows the construction of networks that combine the attributes of ultra high capacity, scalability, flexibility, self-healing, and auto provisioning, with time of day services and bandwidth by the minute, hour, week, or year. An example of such a network is shown in Fig. 1. The core of the network routes wavelengths to and from destination cities. The standard electronic packet routers load the wavelengths at the edge of the network, but the core of the network routes wavelengths, not packets.

The inevitability of such a mesh-based network as opposed to legacy ring-based architectures is driven by the rate of growth of capacity in optical fiber systems. With recent demonstrated capacities of more than 10 Tb/s in a single fiber, core packet routers are clearly incapable of keeping up. As shown in Fig. 2, electronics of any kind doing the switching function at the nodes in high-capacity networks is quickly becoming impractical since the rate of increase of speed and performance of electronics is much slower than optics. Optics for the switching function allows network elements to be built that are smaller, faster, and cheaper with much lower operating power than their electronic counterparts. This is why the all-optical crossconnect is the idea that has launched 100 startups. These network elements are universally agreed on as

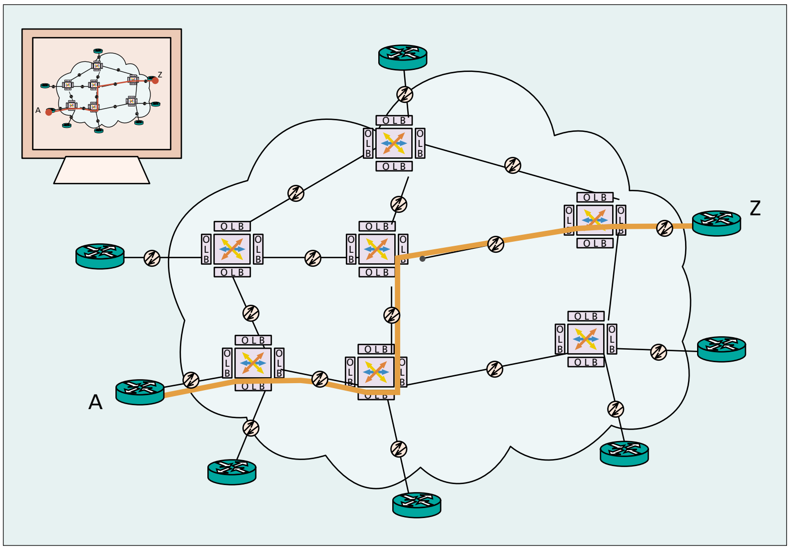

Figure 1. *Example of a mesh-based network architecture that uses large regions of optical transparency of the type allowed by ultra-long-haul transport systems and all-optical crossconnects. This type of network allows for rapid provisioning, auto-restoration, and virtual private networks (VPNs).*

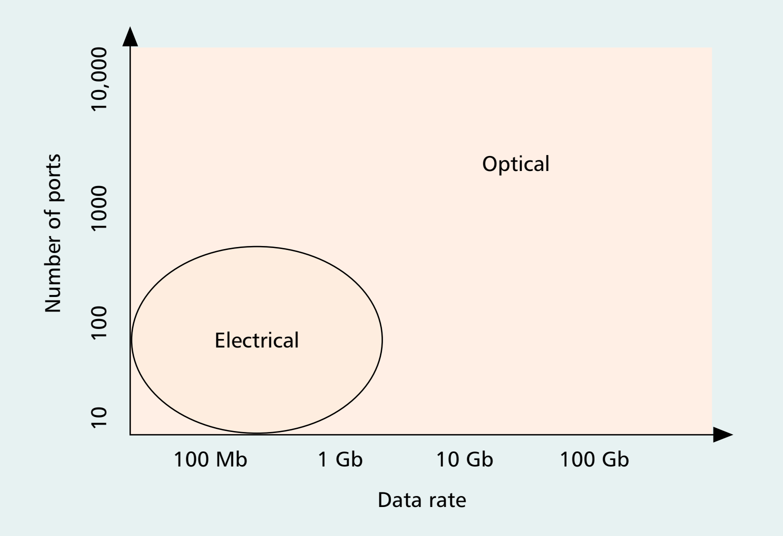

Figure 2. *This diagram shows the design space for electronic vs. all-optical crossconnects. For large port counts and high data rates, the all-optical approach is superior in terms of cost, electrical power consumption, space, and scalability.*

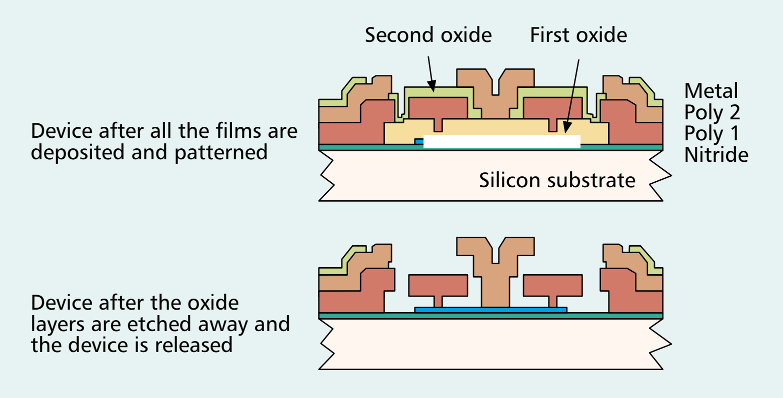

Figure 3. *Shown is a surface micromachining process typically used to build MEMS devices. This figure details the process used by Cronos, now a subsidiary of JDS Uniphase.*

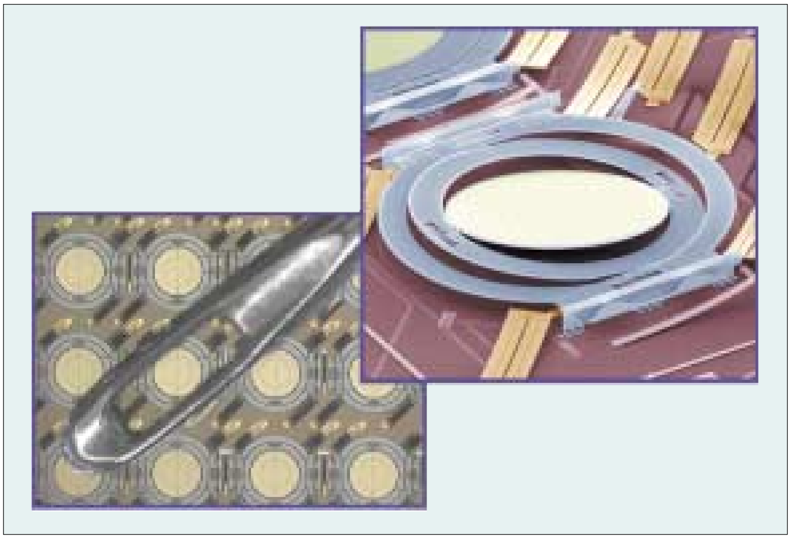

Figure 4. *Two images of MEMS-based OXC mirrors used in the Lucent LambdaRouter. The image in the upper right is a single mirror, and an array of mirrors is shown in the lower left. An eye of a needle is shown for comparison on the array.*

being the key devices for the next generation of terabit networks.

WHAT ARE MEMS DEVICES?

The technology that allows high-port-count data-rate-independent switches is micro-electro-mechanical-systems (MEMS). As shown in Fig. 3, these are silicon micromachines built just the same way as a silicon integrated circuit. Starting with a silicon wafer, one deposits and patterns materials such as polysilicon, silicon nitride, silicon dioxide, and gold in a sequence of steps, producing a complicated three-dimensional structure. However, unlike an integrated circuit, at the end one releases the device or etches parts of it away, leaving pieces free to move. A typical example uses HF to remove the oxides leaving the nitrides, polysilicon, and metals. These devices offer a number of advantages to systems designers. Because they are built using IC batch-processing techniques, these devices, albeit complicated, are inexpensive to produce because many are fabricated in parallel. Also, they get ever better with time, driven forward by the $200 billion/year very large-scale integration (VLSI) business and its relentless development of new tools, techniques, and processes.

VLSI fabrication techniques also allow designers to integrate micromechanical, analog, and digital microelectronic devices on the same chip, producing multifunctional integrated systems. Contrary to intuition, MEMS devices have proven to be robust and long-lived, especially ones whose parts flex without microscopic wear points. Research in this area has been extremely active over the last decade, producing microscopic versions of most macro-machines. MEMS devices have a number of desirable attributes to offer to the systems architect such as small size, high speed, low power, and a high degree of functionality. In particular, many of us believe that the size scale at which these machines work well make them a particularly good match to optics problems where the devices, structures, and relevant wavelengths range in size from one to several hundred microns.

Another feature that can be designed into these devices is something called self-assembly. This technology allows microscopic springs to assemble complex devices during the release step. An example of this is the optical crossconnect mirror shown on the right of Fig. 4. Springs at the sides, shown as the gold lifting members, assemble the devices during the release step, leaving the device as shown, raised up off of the silicon substrate.

WHERE DO WE SEE MEMS BEING USED IN LIGHTWAVE NETWORKS?

Shown in Fig. 5 is a schematic lightwave system with places shown in red where these devices might find application [1–3]. The possible application areas range from data modulators, variable attenuators, active remote nodes, active equalizers, add/drop multiplexers, optical switches, power limiters, choppers for power measurements, and optical crossconnects. In particular, we see MEMS as a disruptive technology for lightwave networks. By disruptive technology we mean one that abruptly changes how things are done in a preexisting industry. We envision that five years from now MEMS will be the technology of choice for devices ranging from simple things such as variable attenuators to complex subsystems such as optical crossconnects. We see lightwave MEMS as being the first billion dollar application for micromechanics and the first to really revolutionize an industry.

Figure 6 shows some examples of MEMS devices for use in lightwave systems. Starting in the lower left corner is a tilting micromirror for use in a variable attenuator. Clockwise are two images, one of a packaged MARS modulator used as a high-speed variable attenuator, the other of a variant of the MARS device for use as an optical data modulator [4]. Next is an example of a 1 × 2 optical switch [5]. In this device, the light enters from the fiber at the left and either gets reflected to the fiber at the top or the mirror lifts out of the way and the light passes on through to the fiber on the right. The next two photos show examples of two axis tilting micromirrors for use in optical crossconnects, the principal subject of this article. Next is a fully functional optical microscope, an NSOM. Finally in the lower center of Fig. 6 is an array of mirrors for use in a MEMS-based add/drop multiplexer for routing wavelengths in a lightwave system [6].

The MEMS device shown in Fig. 4 is the heart of the optical crossconnect switch fabric for the Lucent LambdaRouter. The device is a two-axis tilting micromirror. The picture in the upper right corner of Fig. 4 is a closeup of a mirror, and the picture in the lower left shows an array of mirrors on a silicon substrate. In operation, the gold lifting springs raise the mirrors up off the substrate. The mirror is doubly gimbaled so that it can rotate around two axes. Under the mirror shown are four electrodes. The mirror is grounded. When a voltage is applied between the mirror and an electrode, the mirror is pulled down toward the electrode. The four electrodes allow the mirror to tilt around the two different orthogonal axes. The yellow center section of the mirror is deposited metal to act as a mirror to reflect light shining on the mirror. The array of devices is shown with the eye of a needle to give an idea of scale. Using the techniques of microfabrication, one can build large arrays of identical mirrors on a single silicon substrate. Such arrays of mirrors can then be used to construct large switch fabrics.

The arrays of mirrors are then packaged in LambdaRouter packages, as shown in Fig. 7, which provide the proper environment for a robust long life. The challenges of designing such a package are considerable given the simultaneous requirements of getting many electrical leads as well as light into and out of the package. Figure 8 shows how a switch fabric can be constructed using arrays of MEMS tilting micromirrors. The upper part of Fig. 8 shows a fabric using a single mirror array and a fiber/lens array. The lower part of the figure shows a symmetric design using two mirror arrays and two fiber/lens arrays.

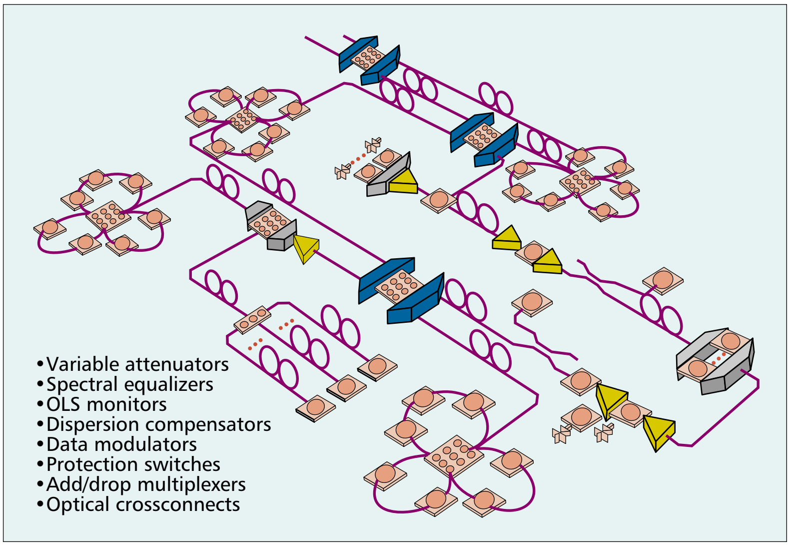

Figure 5. *This diagram shows where in lightwave systems where we feel MEMS devices (indicated in red) will be the technology solution of choice for network architects.*

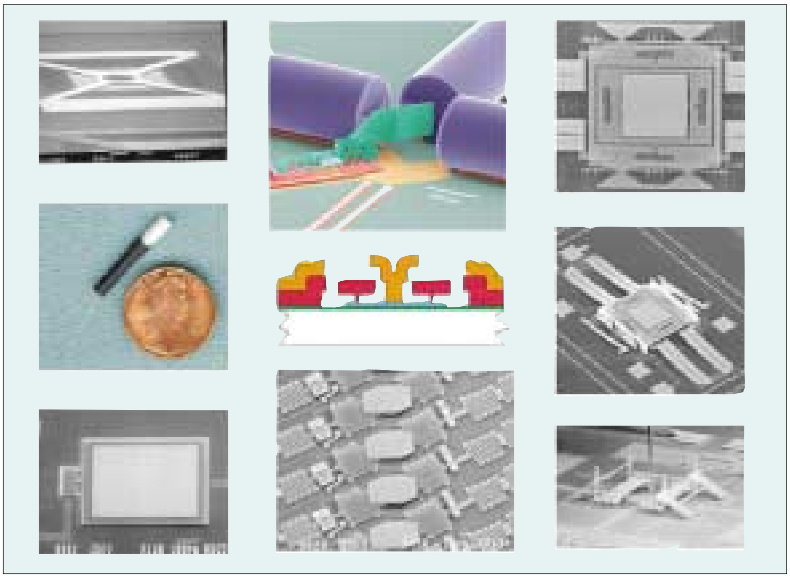

Figure 6. *This figure shows some examples of typical MEMS devices for use in lightwave systems. Starting from the upper left and going clockwise is shown a MARS device, a 1 × 2 optical switch, a two-axis tilting micromirror for use in an OXC, another view of the OXC mirror, an NSOM, a mirror array for use in an add/drop multiplexer, a tilting mirror for use in a variable attenuator, and a MARS variable attenuator.*

In operation the input signals arrive via optical fibers in a fiber array. A lens array creates collimated beams that then land on micromirrors, which can redirect the beams. They can either go to a single fixed reflector (upper half of Fig. 8) or another mirror array for a symmetric fabric. By adjusting the angles of the input and output mirrors, any input can be connected to any output. Fabrics built this

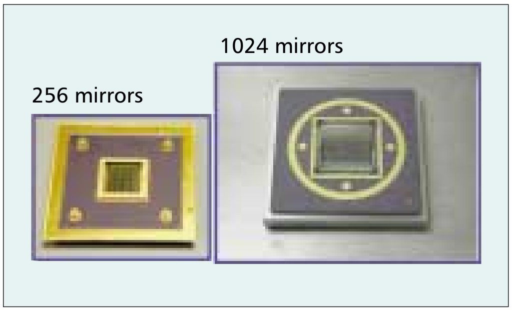

Figure 7. *Two packaged MEMS mirror arrays for use in optical switch fabrics.*

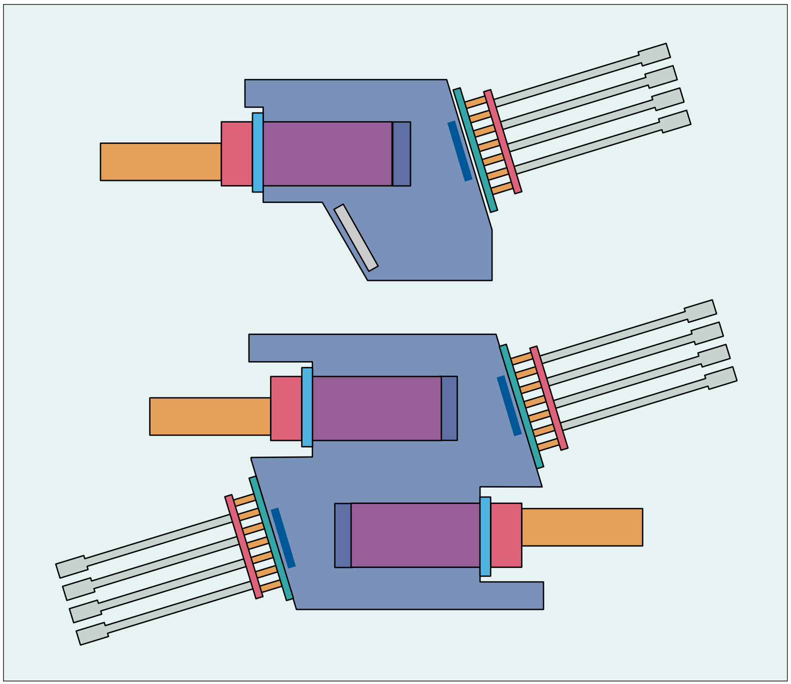

Figure 8. *Two different designs for MEMS-based OXC fabrics. In the upper design, a fixed folding mirror is used; in the lower symmetric design the mirror is dispensed with. In both designs, a fiber array is fastened to a lens array to produce a grid of collimated beams that are then redirected by the MEMS mirrors in the array to point to the designated output fibers.*

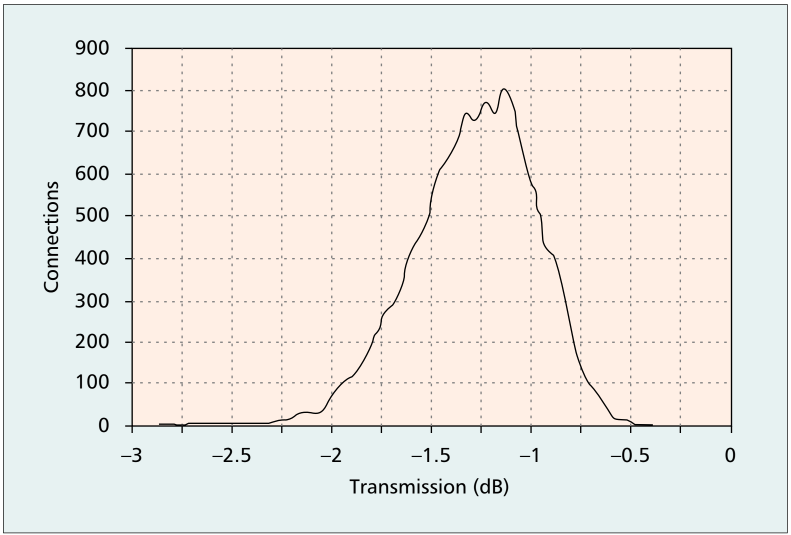

Figure 9. *Histogram of the loss distribution for a typical MEMS-based switch fabric. Note both the low average loss and the narrow distribution of losses.*

way are data-rate-independent, can operate over the entire 1.3–1.6 μ optical communications band, have negligible PMD and PDL, and have very low optical losses. The losses for a typical fabric designed for use in a LambdaRouter are shown in Fig. 9. The average loss is ~1.25 dB with a very narrow distribution about that average. Lightwave systems tend to be built with very narrow specs for dynamic range, so low average loss as well as a narrow distribution are critical. MEMS-based switch fabrics are capable of meeting these demanding specs. Few if any other technologies are capable of this type of performance. This is one of the reasons for the commercial success of the LambdaRouter system.

Shown in Fig. 10 is an assembled LambdaRouter switch fabric of 256 × 256 size. The final size of the fabric enclosure is dominated by the need to find room on a panel for all the optical connectors. The basic fabric itself is very small. Clearly the optical connector industry will need to build high-density low-loss connectors driven by the needs of such fabrics.

Figure 11 shows the complete LambdaRouter network element built using the switch fabrics shown in Fig. 10. The system is a full duplex optical crossconnect with two switch fabrics, HVDACS, optical monitors, and a system controller to control it all. Such systems have been commercially deployed for over 18 months. The Lucent LambdaRouter is a fully NEBS level 3 compliant system and has passed all of the most rigorous tests for the most demanding telecom applications. Such systems are now beginning to be widely commercially deployed.

One of the key advantages of the MEMS technology as a way to build large all-optical crossconnects is that they are scalable. They are scalable in both data rate, because they are optically transparent, and port count. Multithousand port fabrics appear to be readily buildable. Shown in Fig. 7 is both an array with 256 mirrors as well as one with more than 1000 mirrors. Such large mirror arrays allow the construction of crossconnects with more than 1000 input and output ports.

Shown in Fig. 12 is an example of such an optical switch fabric for a 1024-port LambdaRouter. The fabric uses the mirror arrays shown in Fig. 7. These fabrics combine small size, low cost, low loss, and vast capacity. These fabrics have a demonstrated capacity in excess of 2 Pb/s [7]. While electronic fabrics are struggling to reach an aggregate capacity of 1 Tb/s, all-optical fabrics such as these have a capacity more than 2000 times larger. As the networks of the future get built out with hundreds of WDM channels on dozens of fibers at major metropolitan nodes, MEMS-based optical switch fabrics such as the Lucent LambdaRouter will be the only way to switch that much data.

CONCLUSION

Silicon micromechanics is a field that is just beginning to impact many areas of science and technology. In fields as diverse as the automotive industry, aeronautics, cellular communications, chemistry, acoustics, display technologies, and lightwave systems, these highly functional devices are making a big name for themselves despite their diminutive size. In this article we show how we believe they will enable lightwave systems designers to build highly functional devices to keep up with the explosive growth in bandwidth. It appears to us that the future of lightwave systems belongs to MEMS.

REFERENCES

For a general reference on MEMS in a wide range of application areas, see *MRS Bulletin* Special Issue on Microelectromechanical Systems: Technology and Applications, Apr. 2001, vol. 26, no. 4.

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BIOGRAPHIES

DAVID BISHOP (djb@lucent.com) graduated from Vicenza American High School, Vicenza, Italy, in 1969. In 1973 he graduated Magna Cum Laude and with honors from Syracuse University with a B.S. in physics. In 1977 he received an M.S. in physics from Cornell University and in 1978 a Ph.D. in physics from Cornell. In 1978 he became a postdoctoral member of staff at AT&T-Bell Laboratories and in 1979 was made a member of technical staff. In 1988 he was made a Distinguished Member of Technical Staff, and later that same year was promoted to department head, Bell Laboratories. He is a Bell Laboratories Fellow and is currently the optical research VP, ONG and VP, Communications Subsystems Research Laboratory, Bell Laboratories, Lucent Technologies, responsible for leading the MEMS development effort at Lucent Technologies.

RANDY GILES (randygiles@lucent.com) is director of the advanced photonics research department at Lucent Technologies. Research programs in his department include the study of new optical materials, the characterization and utilization of light in optical communications, and the development of optical networking technologies. In his 15-year career at Bell Laboratories, he pioneered the modeling and use of erbium-doped fiber amplifiers for lightwave systems, demonstrated the first optical add/drop multiplexers by means of Bragg-grating technology, and developed optical network applications of micromachines including scalable optical crossconnects and add/drop multiplexers. He is a graduate of the Universities of Alberta and Victoria in the study of intense laser-plasma interactions. Before Bell Laboratories, he worked at Nortel's research labs on their first gigabit optical transmission systems.

GARY P. AUSTIN [M] (gpa@lucent.com) is general manager of the Optical Switching Systems Business Unit within the Optical Networking Group at Lucent. He manages the various aspects of productizing the WaveStar LambdaRouter. His career with AT&T and subsequently Lucent includes work at Bell Labs and management positions in transmission and optical networking systems development. Austin holds B.S. and M.S. degrees in electrical engineering from Tennessee Tech and Stanford University, respectively.

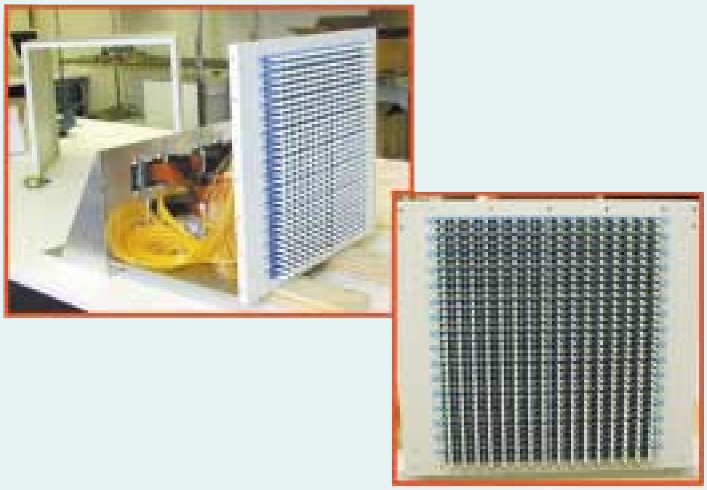

Figure 10. *Optical switch fabric built using the MEMS arrays shown in Fig. 4. This is a Lucent LambdaRouter fabric array used in the system shown in Fig. 11.*

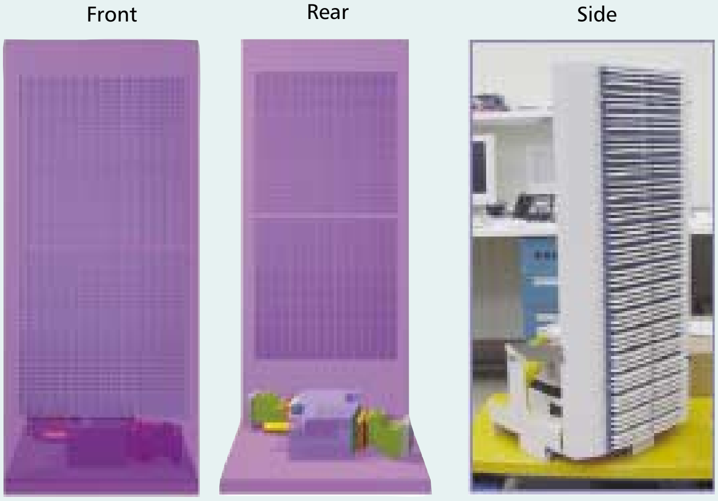

Figure 12. *The industry's first 1024-port optical switch fabric built using MEMS devices. It has a demonstrated aggregate switching capacity of more than 2 Pb/s.*

Figure 11. *Lucent LambdaRouter optical crossconnect system. The system is fully NEBS level 3 compliant and is beginning large-scale commercial deployment.*