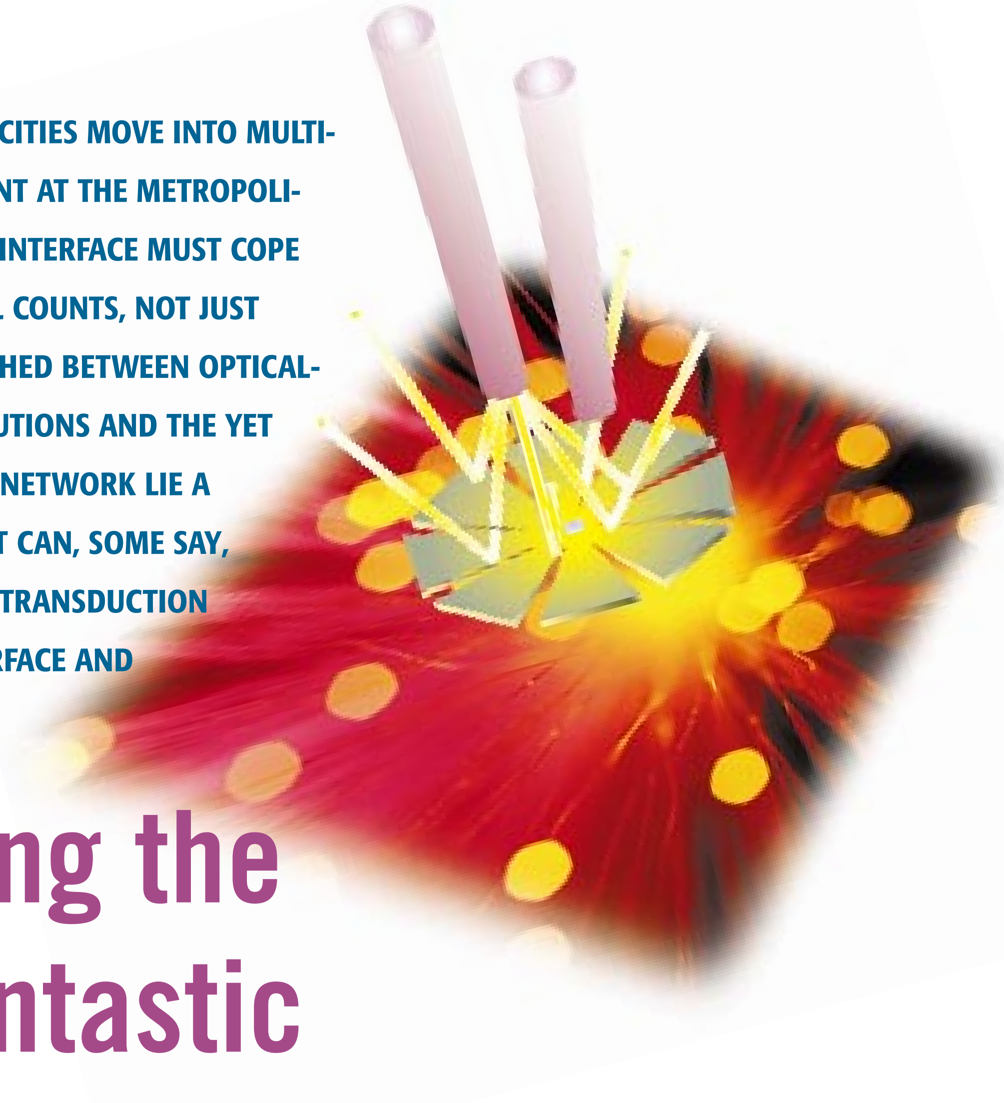
By Joshua Israelsohn, Technical Editor

AS FIBER CARRYING CAPACITIES MOVE INTO MULTITERABIT RATES, EQUIPMENT AT THE METROPOLITAN-SERVICE/LONG-HAUL INTERFACE MUST COPE WITH GROWING CHANNEL COUNTS, NOT JUST CHANNEL SPEEDS. STRETCHED BETWEEN OPTICAL-ELECTRICAL-OPTICAL SOLUTIONS AND THE YET UNREALIZABLE ALL FIBER NETWORK LIE A NUMBER OF DEVICES THAT CAN, SOME SAY, PUSH ELECTROPHOTONIC TRANSDUCTION TO THE ENTERPRISE INTERFACE AND PERHAPS TO YOUR DOOR.



# Switching the light fantastic

Unlike their MEMS counterparts, which evolved primarily through the application and advancement of traditional semiconductor processes, MOEMS (micro-optical electromechanical-systems) technologies are enjoying a second set of technical drivers—this time from the photonics industry. The comparatively rapid development of practical deployable devices owes much to this added push. The drive behind MOEMS, however, is hardly restricted to the technical. The growth rate of communications infrastructure constitutes a substantial economic force. Add to that the limited performance of alternative technologies, and it appears that we well may have means, motive, and opportunity—the signature of a killer technology (see sidebar "Son of MEMS?").

Fiber for long-haul DWDM operates primarily in the C band (1530 to 1570 nm) and more recently in the L band (1570 to 1610 nm). Channel spacings of 0.8 nm (100 GHz) are giving way to 0.4 nm (50 GHz) as efforts to pack more channels onto a single fiber strand succeed. Fundamental system components at this level provide facility for emission, detection, amplification, and routing. They must exhibit flat spectral responses over a broad bandwidth and require little if any further equalization (**Reference 1**).

## AT A GLANCE

- ▷ The current trend toward multiterabit long-haul fiber is putting performance pressure on the metropolitan loop. Add/drop multiplexers capable of handling hundreds of channels are necessary for the trend to continue.
- ▷ DWDM switching demands photonic, not electronic, devices. Though planar-waveguide techniques are available, they are not practical for dense switching applications. MOEMS devices, however, are.
- ▷ MOEMS technology is in its early stage of commercialization. Parts are being sold into OEM sockets, however, and the technology is providing functional density and parametric performance hard to find otherwise.
- ▷ Advances in assembling, handling, testing, and monitoring lag behind developments in device and process design. The industry is fragmented with no ready method of establishing standards and norms, impeding support industries from making their contributions to this technology.

## ACRONYMS

**CAIBE:** chemically assisted ion-beam etch
**DWDM:** dense-wavelength-division multiplexing
**InGaAs:** indium-gallium-arsenide
**MARS:** mechanical antireflective switch
**MCM:** multichip module
**MEMS:** micro-electromechanical systems
**MOEMS:** micro-optical electromechanical systems (optical MEMS)
**OEO:** optical-electrical optical
**OXC:** optical cross-connect
**VCSEL:** vertical-cavity surface-emitting laser
**VCVA:** voltage-controlled variable attenuator
**WDM:** wavelength-division multiplexing

One challenge is simply lighting the 100 0.4-nm channels defined in each of the bands. Tunable VCSELs (vertical-cavity surface-emitting lasers) are commonly limited to about a 4-nm tuning range, or 10 channels. Component manufacturers have no more desire to manufacture 10 different tunable emitter models to cover a band than do system operators to pay for stocking the spares. This situation is particularly true when complete modules, including laser, modulator, filter, and locking circuitry cost in the neighborhood of $1000.

To tune a laser, you can mechanically adjust the laser cavity size, thermally adjust the effective optical path length, or electrically alter the characteristics of the laser diode (**Reference 2**). Of these, mechanically adjusting the laser cavity lends itself to a miniaturizable, low-power solution continuously tunable over an entire band.

A good example of a device implementing this method is a tunable laser from CoreTek, now a part of Nortel Networks, which combines a common 980-nm VCSEL diode with MOEMS mirrors to produce a tunable structure centered at 1550 nm. An electrostatic control voltage positions the top mirror, which sits on a supporting membrane. Changes in the control voltage adjust the cavity size and thus the output wavelength (**Figure 1** and **Reference 3**). The device has been demonstrated over a 50-nm range with better than 50-dB side-mode suppression.

This basic theme, using electrostatically controlled movable surfaces to set or adjust a physical dimension in an optical system, recurs in MOEMS modulators, filters, and even switches.

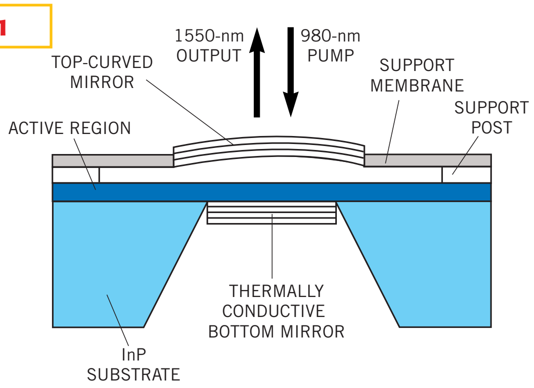
### LIGHTNESS AT THE EDGE OF TOWN

Where long-haul and metropolitan services meet, WDM systems service local channels. Many systems electronically route and level individual channels, converting the signals from the optical to electrical domain and back again. OEO (optical-electrical-optical) systems have a number of factors in their favor: They use a mature electronic technology base, itself advancing under common parametric performance pressures from other industry segments; the industry has better developed infrastructure for assembling, handling, testing, and monitoring dense electronic systems than dense photonic systems; and the limitations of electronic, not optical, systems determine the point at which the limited bandwidth of individual channels gives way to wavelength multiplexing.

The costs of OEO include the natural inefficiencies of two transductions, the power losses associated with handling multigigahertz electronic channels, and the nonzero error rates during the data recovery process, just to point to three. As DWDM becomes increasingly dense, spatial challenges to electronic signal routing also make a strong argument for optical solutions. Perhaps most compelling for flexible systems is that optical channels are agnostic with regard to channel coding, including bit rate and protocol. Systems may allocate and reallocate optical paths to serve signals mutually incompatible in the electrical domain.

A COADM's (configurable optical add/drop multiplexer's) input demultiplexer separates an incoming WDM signal into its individual constituent wavelengths (**Figure 2**). The individual channels feed into a bank of 2×2 switches that allow signals to add to, pass through, or drop from the main signal path. These switches can take a form much like those in the long-haul applications, but here component manufacturers

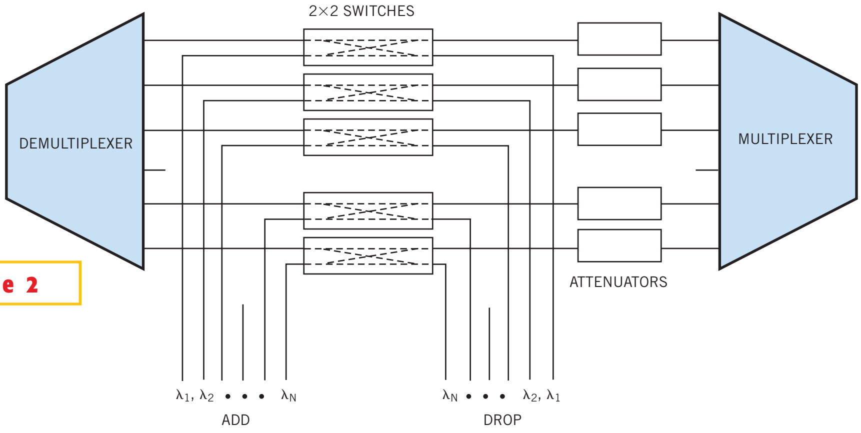
**Figure 1**



**Coretek's tunable MEMS-VCSEL laser operates with a 7-μm spot in the fundamental mode. The 40-μm top-mirror aperture minimizes the laser's diffraction losses.**

can take advantage of the COADM's regular structure and combine N switches into a single matrix.

**Figure 2**



**COADMs at the network interface manage individual wavelengths.**

Like their electronic counterparts, optical systems need a means of controlling signal amplitude. To ensure consistent signal quality across the network, the COADM must prevent single wavelengths from overdriving downstream optical amplifiers and detectors. All signals must be level-matched independently of their origins, local or distant, before the output multiplexer reassembles them into a WDM signal. Beyond gross overload conditions, the system maintains tight level matches

## SON OF MEMS?

The key differences between this early evolutionary stage of MOEMS technology and the equivalent period in the history of MEMS commercialization are at least threefold: market pull, existing infrastructure, and few attractive and well-entrenched competing technologies serving the key applications.

The market pull on the communications industry as a whole has been well-documented. It has both motivated and been enabled by advances in the carrying capacity of individual fiber strands, which increased fairly steadily from 1979 to 1995, doubling every two years. Since 1995, when the first 10-Gbps systems were demonstrated at the Geneva Telecom Forum, that capacity growth rate has been a factor of four per year. This scenario occurred despite the fact that fiber-optic transmission rates were already within two octaves of the practical limits for electronic channels. WDM technologies have allowed the growth curve to continue by packing multiple wavelengths, each an independent channel, onto a single strand (**references A** and **B**).

With growth rates like these, it's difficult to point to the current state of the art. The claim becomes obsolete nearly as one speaks the words. However, to pick a recent milestone, Alcatel last month demonstrated 128 closely spaced, 40-Gbps channels sharing a single strand. This arrangement yielded a 5.12-Tbps, unidirectional DWDM link with a 300-km range (**Reference C**). Meanwhile, as fiber's carrying capacity grows, so does the total length of installed fiber. Current installation rates reportedly passed 50,000 miles per day, which as Lucent Optoelectronics Chief Technology Officer Thomas Koch, PhD, points out, is Mach 3 (**Reference D**).

Ownership of the means of production, not long ago touted as a significant barrier to entry in the microstructure technology/MEMS market, is no longer strictly necessary. Small companies can avail themselves of design, foundry, test, and packaging services on either a turnkey basis or an à-la-carte basis (**Reference E**). Insofar as their providers can smoothly integrate these services into their customer's product-development flow, they can free the product-development team to concentrate on their own core added value and to treat micromachining as a modular technology. This is a recent development though, and the service providers' abilities to deliver are largely untested.

Unlike the early commercialization of MEMS devices, which concentrated on applications for which there were well-entrenched low-tech solutions, many MOEMS devices are competing in areas that didn't exist just a few years ago. With no entrenched competition to displace, it's every technology for itself. With a more level playing field, the contest invites comparisons of size, simplicity of implementation, installed cost, reliability, functional density, and parametric performance (not necessarily in that order) with no technology enjoying a home-court advantage (**references F** and **G**).

MOEMS technology, however, is in its early stages of commercialization. Though there have been a number of noteworthy market successes already, it would be a mistake to underestimate the challenges to successful device design, fabrication, test, and packaging.

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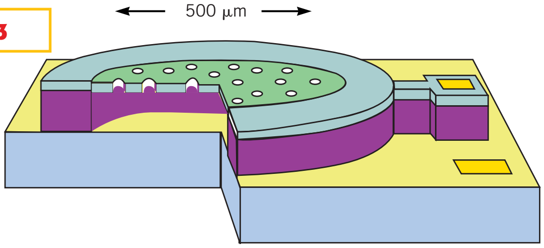
as a means of maintaining a target quality level of service, which systems usually assess by measuring the bit-error rate. Electrically controlled optical attenuators serve this leveling function.

One of several possible approaches is Bell Labs' MARS VCVA (voltage-controlled variable attenuator). Bell Labs has developed a portfolio of experimental MOEMS devices, several of which exploit an actuation mechanism similar to that used by tunable MOEMS lasers. Based on the first of such designs, a small electrostatically actuated reflective/antireflective switch, the MARS VCVA features a reflective surface fabricated on a flexible trampolinelike structure suspended over and separated from the substrate by an air gap (**Figure 3**). The VCVA's optical surface reflects the signal from an input collimator to an output fiber with an insertion loss of 3 dB. The attenuator operates in 3 µsec over a 20-dB range with less than 1-dB gain tilt in a 40-nm bandwidth.

**Figure 3**



Electrostatic displacement of the MARS attenuator reduces the reflected signal by as much as 20 dB over the full 40-nm operating bandwidth.

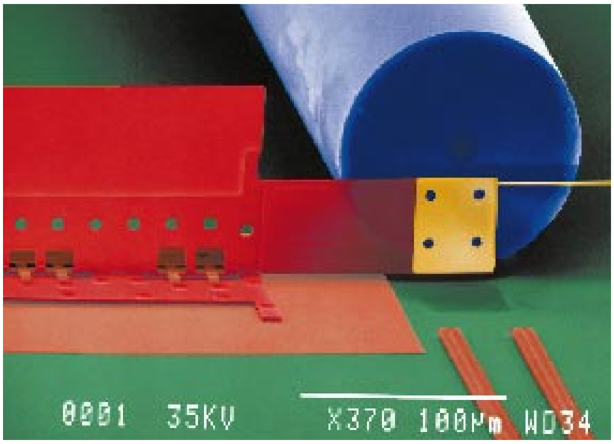


**Figure 4**

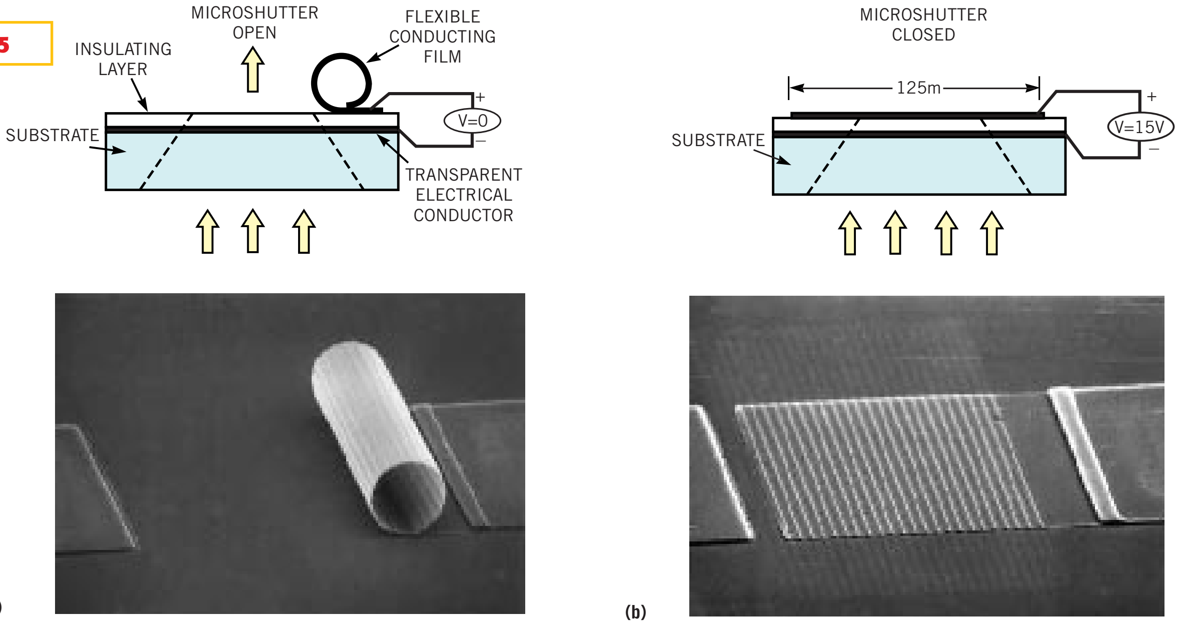
An attenuator based on an electrostatically actuated silicon optical shutter has a 50-dB dynamic range.

Another arrangement, the optical shutter attenuator dispenses with the collimator and trades actuation speed to 100 µsec, for 0.47-dB insertion loss and better than 50-dB contrast ratio. This part mates a pair of coaxial fibers mounted with a 10-µm gap. A silicon shutter moves into the gap, impeding the coupled signal, when a control signal drives a MEMS actuator (**Figure 4**).

## SWITCHING THE LIGHT

Fiber-optic systems must include switches to realize the extreme uptime ratios demanded of the communications network while providing for maintenance, upgrades, and expansion. Simple 1×2 and 2×2 switches provide rudimentary routing services of consolidated WDM signals, both within equipment and between long-haul network nodes. Small-scale MOEMS devices provide reliable switching over billions of cycles with

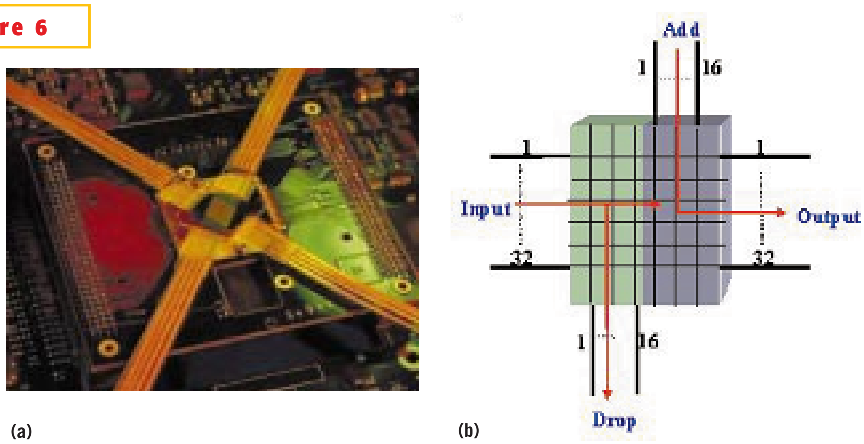
**Figure 5**



Axsun Technologies' roller-shade switch (a), developed under license from MIT Lincoln Laboratory, unfurls an opaque thin film over a hole etched through the substrate (b) (SEMs courtesy MIT Lincoln Laboratory).

no mechanism wear-out or parametric degradation. A typical device of this type, a 1×2 moving-mirror switch from Sercalo Microtechnology, for example, operates over a bandwidth of 1240 to 1600 nm. Crosstalk is better than −50 dB, and insertion loss is less than 1 dB.

**Figure 6**



(a) (b)

The Agilent photonic switching platform combines planar-lightwave-circuit and ink-jet-heater technologies to form a novel switching matrix for COADMs and OXCs (a). Index-matching fluid allows straight-line propagation. When heated, the fluid forms a vapor bubble, which reflects the incident signal into an orthogonal waveguide. The dual-16×32 bubble switch forms the core of a COADM with 32 inputs and outputs and 16 add and drop channels (b).

Axsun Technologies has taken another approach to small-scale switching with its roller-shade switch, now in development under license from the Massachusetts Institute of Technology Lincoln Laboratory (www.ll.mit.edu). Here, an actuating signal causes a thin, reflective, conductive film to unfurl itself over a hole in the substrate by electrostatic attraction (**Figure 5**). Without the actuating signal, stresses built in during fabrication force the thin film to roll itself back up. Axsun has demonstrated examples of 1×2 switches. Larger configurations are also possible using the roller-shade.

Component designers have employed planar-waveguide methods to form a no-moving-parts electro-optical switch. This structure is a logical extension of the lithium-niobate planar modulator (**Reference 4**). Signals from the two inputs mix in a coupler ahead of a pair of waveguides. The refractive index of the central waveguides depend on the bias voltage applied across the lithium-niobate structure. The refractive index determines the delay through the guides. Depending on the delay, the signals switch between an output pair (**Reference 5**). A limitation of this device is that you cannot extend it to configurations larger than 2×2 except by cascading a disproportionately large number of similar cells.

Agilent makes perhaps the most advertised MOEMS device ever, the Agilent photonic switching platform, popularly known as the bubble switch. Agilent deposits a 32×32 or dual 16×32 waveguide matrix on a glass substrate. They etch a gap through the waveguides at each of the 1024 intersections. An index-matching fluid fills the gaps, so at normal operating temperatures, each waveguide acts as a continuous straight path, west to east for the 32 rows and north to south for the 32 columns. To complete the core structure, individually addressable heater elements, borrowed from now-mature ink-jet technology, attach to the glass substrate at each intersection.

Heating a waveguide intersection causes the liquid to form a vapor bubble in less than 10 msec. The bubble reflects incoming signals from the north into the exit waveguide to the east while it blocks incoming signals from the west. The dual-16×32 version of the bubble switch forms the switching core of a COADM with 32 inputs, 32 outputs, 16 add channels, and 16 drops (**Figure 6**). Combining multiple devices forms larger OXC (optical-cross-connect) switching matrices.

Larger OXC switches are appearing,

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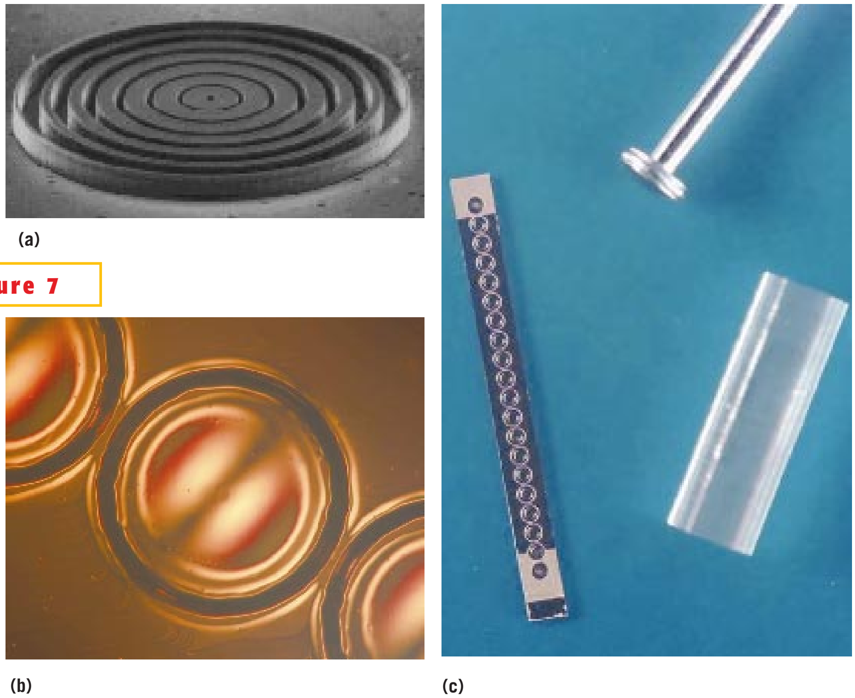
such as 2- and 3-D structures from Optical Micro-Machines. Another moving-mirror arrangement, these form large N×M switching matrices without cascading multiple devices.

### SHAPES OF THINGS TO COME

Currently, most practical manifestations of MOEMS-based devices take the form of hybrids with few fully integrated exceptions. The benefits of integrated photonics are similar to those for electronics: increased speed, reduced power consumption, increased reliability, reduced cost, and scalability.

Even if component manufacturers cannot yet make many fully integrated functions, they can apply microstructure-technology processes to device fabrication to take advantage of smaller regular structures. For example, many packages terminate fiber with collimators, commonly formed by individually cutting and polishing segments of a drawn glass rod. The finished collimators, gradient index devices, typically measure 1.8 mm in diameter and 4 to 5 mm long.

**Figure 7**



(a)

(b)

(c)

**A CAIBE process patterns gallium-phosphide in a novel lens-fabrication process (a). The finished lenses have an operating diameter on the order of 150 μm on 500-μm centers (b). A bar of 20 micro-optic collimators is slightly longer than one device made by a drawn-glass process (c).**

Axsun Technologies is making arrays of collimators using a single-mask, mass-transport technique that can form 2500 lenses on a 2-in. gallium-phosphide wafer with obvious scalability. The procedure can photolithographically shape lenses over a broad range of designs, in much the same way that standard semiconductor methods control device parametrics through pattern geometry and controlled-process conditions. In this case, however, the patterning and process control go to making micro-aspheric and micro-anamorphic optics. A CAIBE cuts the exposed pattern into the gallium-phosphide wafer leaving a 2-D binary distribution of material. A mass-transport bake in a controlled atmosphere forms the finished lens array (**Figure 7**). A final coating step applies either an antireflective or a reflective layer, depending upon whether the formed parts are lenses or mirrors. The advantage of fabricating lens arrays goes well beyond the economies of the devices themselves, though approaching a two-orders-of-magnitude cost benefit is attractive in its own right. Coplanar optics on fixed precision centers can greatly simplify the termination of multiple fiber functions, such as even moderate-sized cross-connects.

Though systems electrically power and control active photonic devices, a photogenerator developed at Bell Labs suggests that in the future component makers could implement some functions as optically powered devices. Optical power regulators and limiters fit this kind of arrangement particularly well, though switching functions are also possible. Combining the MEMS optical shutter attenuator with an InGaAs photogenerator, Bell Labs has demonstrated signal-powered limiters with 12-to-1 dB/dB compression ratios. They have also demonstrated all optical switches that operate on as little as 3 μW from a control fiber and a long wavelength source.□

You can reach
Technical Editor
Joshua Israelsohn
at 1-617-558-4427,
fax 1-617-558-4470,
e-mail
jisraelsohn@
cahners.com.

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