

Silicon micromechanics takes on light-wave networks

Silicon micromechanics is penetrating an increasing number of technologies. In areas as diverse as chemistry, wireless communications, acoustics, data storage, imaging, automobiles, inertial navigation, and now fiber-optic communications, scientists and engineers are building devices with the poten-

tions in optical communications.

MEMS research grew out of the vast capabilities developed by the semiconductor industry, including deposition, etching, lithography, and an array of chemical processes, such as those using highly selective etching chemicals that have different etch rates for

are economical to produce because many are made simultaneously. In addition, designers and manufacturers can exploit the extensive capabilities of the IC-fabrication industry and can profitably use previous-generation equipment. When a billion-dollar IC factory becomes obsolete in less than five years, the ability to reuse equipment for a new class of cutting-edge products is compelling.

IC-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. Research in this area during the last decade has yielded microscopic versions of most macromachines. In particular, the size scale at which these machines work makes them a particularly good match to optics problems, where the devices, structures, and relevant wavelengths range in size from one to several hundred micrometers.

At Bell Labs, optical MEMS research has focused on devices such as optical modulators, micromirrors, and arrays of tilting micromirrors. However, perhaps the single most powerful device built there is a simple optical switch (Figure 1). The switch allows the building of a wide variety of devices and systems. These include wavelength add-drop multiplexers (used to add or remove different wavelengths from the flow of light in an optical fiber), positioning switches, optically powered remote nodes, power limiters, variable attenuators, and wavelength-division multiplexed (WDM) signal equalizers used to maintain the strength of the signal. The optical switch offers a single building block that enables optical scientists to take a modular approach to building complex systems from simple, well-understood elements.

MEMS optical switch

Figure 2 illustrates the principle behind this multipurpose optical switch. It consists of a polysilicon, gold-plated mirror connected by an arm to a parallel-plate actuator on the right-hand side of the image. The device works like a seesaw with the pivot point located where the arm attaches to the plate.

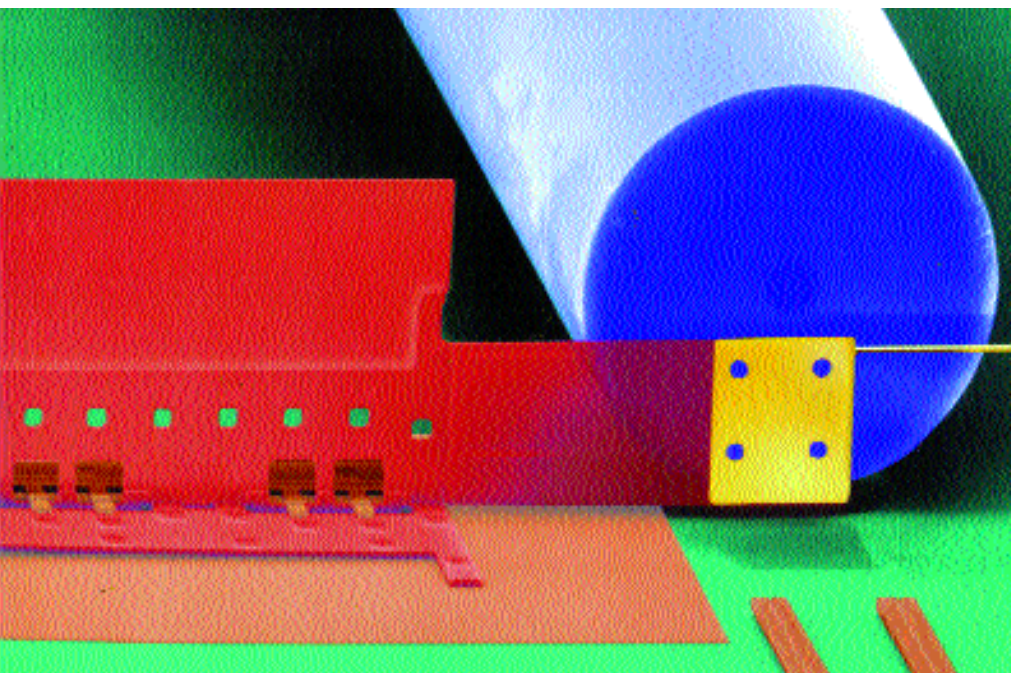


Figure 1. When the gold mirror on the polysilicon plate is placed into the beam, the mirror blocks the light and reflects it back into the fiber from which it came.

tial to radically alter their industries.

The rapidly expanding demand for broadband data communications and the unrelenting pressure to reduce costs have made optical MEMS (microelectromechanical systems) an extremely active area of research and development. This interdisciplinary technology draws on expertise in physics, chemistry, electrical engineering, computer science, materials science, and mechanical engineering. Marketing experts predict a multibillion-dollar growth for optical MEMS devices. In the coming decades, many physicists will find employment creating the new technology that promises to facilitate innova-

different crystallographic orientations and materials. These processes, which researchers originally developed to build microelectronic devices, also enable the creation of micromechanical devices, that is, structures capable of motion on a microscopic scale.

Building MEMS devices essentially relies on the techniques used to produce silicon integrated circuits. Various films—such as polysilicon, silicon nitride, silicon dioxide, and gold—are deposited and patterned to produce complex, multilayer, three-dimensional structures. The major difference in fabrication occurs at the end of the MEMS process. A selective etch removes some of the layer materials, which leaves a device with movable elements.

MEMS devices offer a number of advantages to designers. They are made using integrated circuit (IC) batch-processing techniques, so although fabrication may be a complicated, multistep process, the devices

In the absence of an applied voltage, the gold mirror rests below the waveguide cores of two closely spaced fibers (only one is shown in the drawing), and light is transmitted from one fiber to the other with very little loss. Applying a few volts between the actuator plate and

actuation, is ideally suited for its low-power operation. Many applications require the switch to change state only infrequently. Even those situations needing frequent reconfiguration require little electrical power, typi-

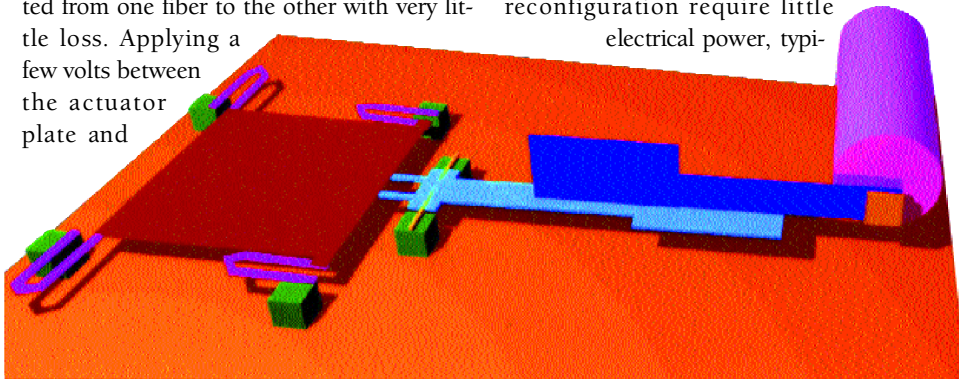


Figure 2. When a voltage is applied between the actuator (red plate) and the substrate, the actuator is pulled down, also pulling the long blue arm that is pivoted around the yellow rods, thus moving the gold plate into the light path.

the substrate pulls the plate down toward the substrate. The pivot forces the arm off of the substrate and lifts the gold mirror into the light path between the two fibers, reflecting light back down the fiber from which it originally traveled.

Two key attributes of the MEMS reflective switch are its thin silicon shutters and low-voltage electrostatic actuators. The thin shutters, made of a gold layer deposited on a single polysilicon layer, are less than $5\ \mu\text{m}$ thick and can be inserted into a narrow gap between two optical fibers to serve as a routing mirror. Fiber-to-fiber losses of light of less than 10% have been demonstrated in these MEMS switches with active (adjustable) fiber alignment, and 16% with “passive” assembly, which simply uses guide rails to position the fibers. In addition to reducing the loss of light at the insertion, the narrow gap limits the optical spot size through the free-space region between fibers, enabling the units to act as extremely effective on-off switches. They completely eliminate unwanted signal leakage that could otherwise lead to interference and crosstalk.

The switch’s second attribute, electrostatic

actuation, is ideally suited for its low-power operation. Many applications require the switch to change state only infrequently. Even those situations needing frequent reconfiguration require little electrical power, typically below $2\ \mu\text{W}$. Low power consumption is highly desirable in dense switch configurations because it greatly reduces the amount of heat generated. Low electrical-power demands also open an array of new applications not previously possible, such as optically powered MEMS circuits. Indeed, this basic optical switch can be used in a wide range of devices and systems.

Switch applications

As optical fibers become more common in the home and at the desktop, the networks that route and deliver information over them have become more complex. The emerging WDM optical-fiber networks—which unlike traditional optical-fiber networks carry data on many wavelengths rather than as one stream at a single optical frequency—are evolving away from high-speed, point-to-point data pipes to intricate optical webs. Such networks will give service providers many advantages, including flexibility with allocating bandwidth and rerouting data streams as needed to bypass damaged lines.

However, making such networks a reality requires a WDM add-drop multiplexer that can route the various WDM channels at every node in the network. In its simplest version, such a multiplexer is a four-port

device consisting of an entering input fiber, an exiting through-fiber, a drop-fiber for removing data streams, and an add-fiber for inserting data. In a WDM system, each data channel is a different optical wavelength. Each wavelength needs to be routed correctly at each node to either the through-port or the drop-port, where data is either accepted or rerouted in a different direction. If a particular wavelength is dropped at a node, it can be reused to transmit a new flow of data.

Individual reflective MEMS switches can work as simple binary-state devices to route optical beam paths within an add-drop multiplexer. Recently, we demonstrated a hybrid, 16-channel, WDM add-drop multiplexer, in which each channel was separated by 0.8 nm. The device used 16 individually packaged MEMS switches. This add-drop multiplexer processed eight wavelengths as drop-and-continue channels (which are used to remove data streams and route them onto other optical fibers) and eight as local drop-and-detect channels. The eight drop-and-detect channels were demultiplexed with the input router and split to enable simultaneous signal reception and pass-through.

This example of a reconfigurable add-drop multiplexer using MEMS optical switches and shutters illustrates the power of MEMS technology to inexpensively create large numbers of these devices, packaged either individually or in arrays. However, MEMS switches also have significant applications as single-unit components, such as power regulators and optically powered switches. Future light-wave networks may need optical-power regulators to minimize crosstalk in network elements and to equalize channels originating from different points in the system.

In modern light-wave networks, one would like both the control signals and the data signals to be transported in a single optical fiber. An all-optical switch could be actuated with light from a separate control channel to reconfigure a node in the network without the need for conventional electronic circuits to detect and process the control signal. With this in mind, we have demonstrated a light-actuated, micromechanical photonic switch (LAMPS) consist-

ing of a MEMS switch electrically driven by a long-wavelength photogenerator. The integrated photogenerator—eight small-area, series-connected InGaAs (indium gallium arsenide) photodiodes arranged in a pie shape—produced sufficient voltage to drive a low-voltage MEMS switch when illuminated with only $2.7 \mu\text{W}$ at 1,500 nm.


This is a modest amount of light, easily delivered hundreds of kilometers through an optical fiber. Although no commercial applications exist yet for the LAMPS circuit or similar optically powered circuits, exciting opportunities have opened up for the provisioning, monitoring, and protection of light-wave networks at optically powered nodes or inaccessible locations.

Optical challenges ahead

The optical MEMS switch described here

illustrates various light-wave network applications that benefit from the small size, scalability, low power consumption, and low cost of MEMS optical circuits. Rapid developments in optical MEMS technology are being driven by the immediacy of challenging optical-network requirements. For example, now that rudimentary nonreconfigurable WDM optical add-drop multiplexers have been deployed in the field, the industry fervently wants to upgrade multiplexers to fully reconfigurable devices. MEMS optical switches meet the functional requirements for these complex optical subsystems and may provide the only practical solution to meeting the coming need for large numbers of add-drop channels.

Although no MEMS device has yet been deployed in an active light-wave network, the wealth of new capabilities presented by

MEMS optical devices places them as certain candidates for imminent commercial success. With the optical MEMS industry projected to become a multibillion-dollar business in five years, many companies have identified MEMS as a strategic technology they cannot afford to neglect, and one that will provide exciting challenges for physicists for many years to come. 

B I O G R A P H Y

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