SILICON MICROMACHINING IN RF AND PHOTONIC APPLICATIONS

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ABSTRACT

Texas Instruments has developed membrane and micromirror devices since the late 1970s. An eggcrate-spacer membrane was used as the spatial light modulator in the early years. Discrete micromirrors supported by cantilever beams created a new era for micromirror devices. Torsional micromirror and flexure-beam micromirror devices were promising for mass production because of their stable supports. TI's digital torsional micromirror device is an amplitude modulator (known as the digital micromirror device or DMD) and is in production development, discussed elsewhere. We also used a torsional device for a 4 × 4 fiber-optic crossbar switch in a 2 cm × 2 cm package. The flexure-beam micromirror device is an analog phase modulator and is considered more efficient than amplitude modulators for use in optical processing systems. TI also developed millimeter-sized membranes for integrated optical switches for telecommunication and network applications. Using a membrane in RF switch applications is a rapidly growing area because of the micromechanical device performance in microsecond-switching characteristics. Our preliminary membrane RF switch test structure results indicate promising speed and RF switching performance. TI collaborated with MIT for modeling of metal-based micromachining.

This talk will provide an overview of developments in metal-based micromechanical devices for RF and photonic applications at Texas Instruments.

I. INTRODUCTION

In the 1970s, TI start using a microelectronic process to develop micromachining structures for spatial light modulators (SLMs). The concept of micromachining was just beginning,[1] and researchers hoped its application to spatial light modulators would help implement optical systems that would provide a breakthrough for information processing.[2,3] In a 10-year period, TI successfully demonstrated several versions of spatial light modulator based on microelectronics/micromirror technology. In the early 1990s, TI invested heavily in production display and printing systems. Meanwhile, other micromirrors and structures were studied within TI to adapt to a wide variety of applications. Larger torsional mirrors were used in fiber-optic switches.[4] Millimeter-sized membranes were used in integrated optic switches.[5,6] Flexure-beam micromirror devices were developed for highly efficient optical correlators.[7] Also, broader aspects of micromachining technology were revisited and prospered in the late 1980s.[8,9] Applications for micromachining in sensors and actuators were introduced at explosive speed. The concept of creating a three-dimensional structure enable by microelectronic batch production brought enormous opportunity to replace existing macrostructures or to develop a new device for new system solutions. TI is also looking into using the same material system for non-optical applications such as an RF switch. During development of the membrane-based RF switches, our test structures gave encouraging results. Micromachine modeling is an important link to transition our research into production. TI established a partnership with MIT to model the devices we fabricated.

DMD applications in projection displays and hard copy systems are described in other publications.[10,11] Torsion micromirror devices have a similar structure to DMDs, and can be used in fiber-optics switches, which are described in Section II. The flexure-beam micromirror device is another promising micromirror structure for production because of its symmetrical support architecture.[12] This device can be used in many optical information processing applications, as elaborated in Section III. The millimeter-sized flexure-beam membrane can be used in modulating cladding layers of waveguides and changing the propagation properties of integrated optics, as explained in Section IV. Section V provides information about RF switch applications for drumhead devices. Section VI describes the newly established MEMCAD system imported from MIT.

II. TORSIONAL MICROMIRROR IN FIBER-OPTIC APPLICATIONS

TI has developed several versions of fiber-optic crossbar switches using micromirror devices.[4] The first version was set up on an optical table and demonstrated video conferencing. The 4 × 4 crossbar fiber-optic switches consist of 16 switching nodes. Each node uses a pair of fibers, microlenses, and one torsional micromirror (Figure 1). The beam from the incoming fiber focuses on the torsional mirror. The mirror is operated at a binary position: the "on" position reflects the beam into the outgoing fiber through microlenses, and the "off" position deflects the light away. The first version took too much space and was not portable. In the second version, we moved toward manufacturability and portability. The incoming and outgoing fibers are aligned through lithography and orientation-dependent etch that form "V"-grooves for fiber positioning and reflection facets for optical beams (Figure 2). The micromirror becomes the only non-integrated part. The substrate is 2 cm × 2 cm silicon material. The third version is under Advanced Research Projects Agency (ARPA) contract to integrate micromirrors on the substrate. In the "off" state, we use a large asymmetrical micromirror to block the beam path that is parallel to the surface (Figure 3).

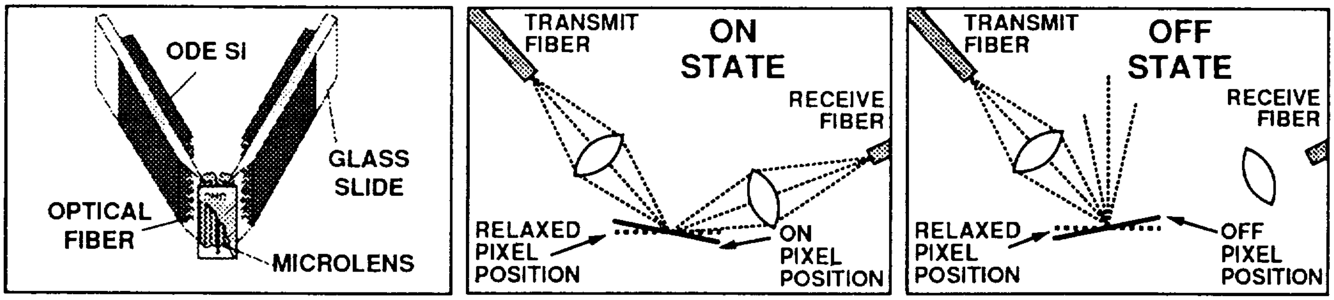

Figure 1. Optical table version of micromirror-based fiber-optic crossbar switch.

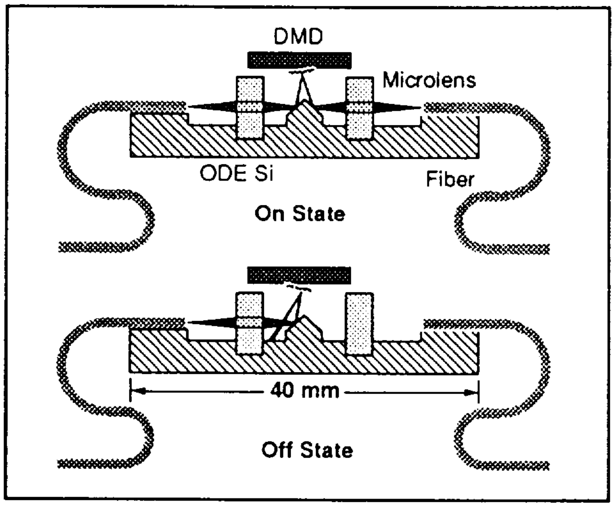

Figure 2. Fiber-optic crossbar switches with fiber on defined-groove substrate and micromirror on a separate chip.

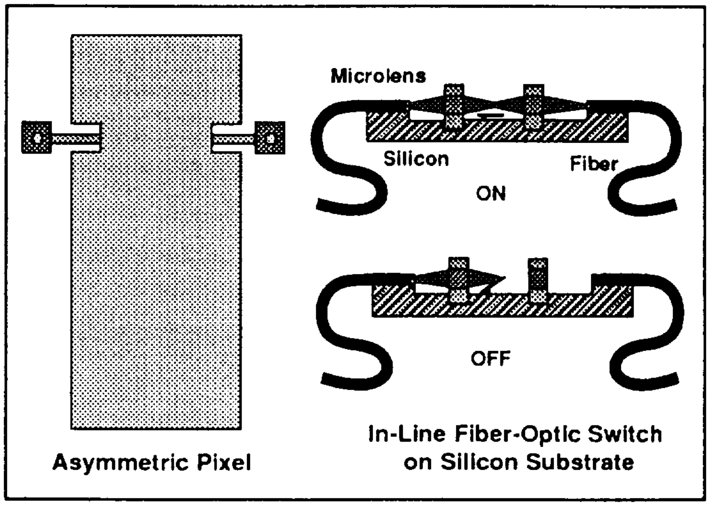

Figure 3. Fully integrated fiber-optic crossbar switches using asymmetric micromirror as shutter.

III. FLEXURE-BEAM MICROMIRROR DEVICES AND APPLICATIONS

The basic structure of the flexure-beam micromechanical element that we implement in this research is shown in Figure 4. The mirror element consists of a square reflecting plate attached at four points to L-shaped flexure hinges. The hinges are attached to four posts that provide the main mechanical support and electrical contact for the element. Each post also mechanically supports four hinges that attach to four different mirrors. The pixel is attracted downward by electrostatic force when it is addressed. The vertical motion of the mirror changes the length of the optical path at the pixel and hence the phase information.

A long list of applications has been waiting for this device. The best known application for the flexure-beam micromirror device is optical correlation.[13,14] Figure 5[15] illustrates a joint transform correlator using two micromirror devices, one as input and one as filter plan, and fold the optical path to use one set of Fourier lenses.

Another application that uses Fourier transform is the spectrum analyzer.[16] Figure 6 shows a spectrum analyzer. A receiver converts a serial incoming signal containing a mixture of different frequencies. A peripheral electronic sample-and-hold circuit maintains the signal at a high enough rate to recognize the waveform. The discretized analog signal is then loaded on the 2-D micromirror SLM. A Fourier lens reveals spots at locations associated with the frequencies.

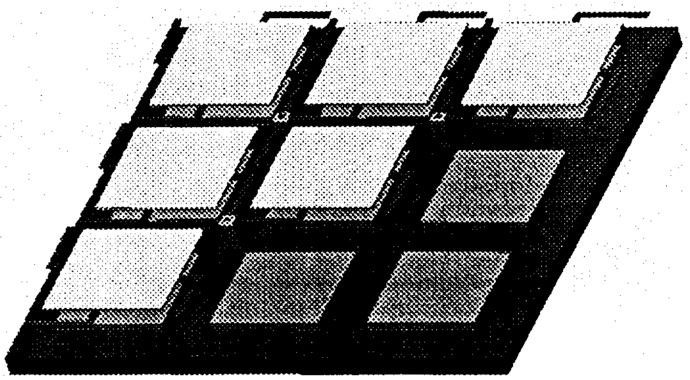

Figure 4. Perspective view of the flexure-beam DMD element.

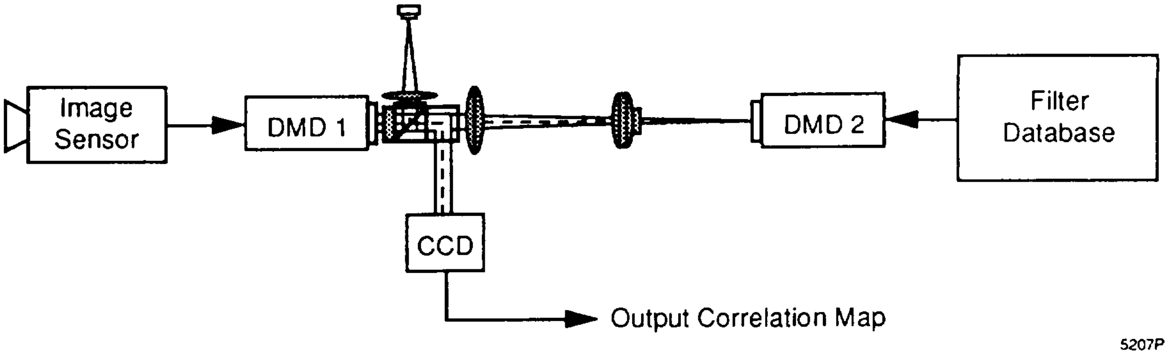

Figure 5. DMD optical correlator.

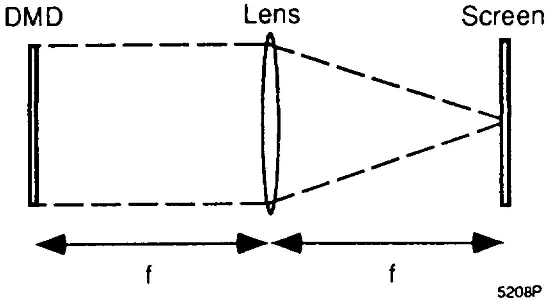

Figure 6. Spectrum analyzer.

Optical interconnects using micromirrors and computer-generated holograms (CGHs)[17] will provide a solution to the bottleneck of massively parallel computing. Figure 7 illustrates the basic concept of the micromirror/CGH interconnect system. The proposed scheme uses the interference property of coherent light. Figure 7 shows the basic interconnection scheme with an example of two processing elements (PEs). The laser in PE1 sends a beam to spot "a" on the CGH. The CGH diffracts this beam into three beams that impinge on the IC plane: one is sent to the SLM and reflected to spot "b" in the CGH plane; two others, a1 and a2, are sent to detectors 1 and 2, respectively. The CGH is constructed so that there is no phase change in a1, a2, and b1 and a 180-degree phase change in b2. If the SLM does not modulate the phase of the beam reflected to "b", the beams interfere constructively at detector 1 and destructively at detector 2. If the SLM modulates the phase on the beam reflected to "b" by 180 degrees, destructive interference occurs now at detector 1, and detector 2 receives the signal associated with constructive interference. If we expand communication to a network of four PEs, we need two SLMs in each PE. There are a total of four different combinations to select the optical paths with two modulators. The number of SLMs, M, needed for interconnecting N PEs is:

$$M = 2 \cdot (\sqrt{N} - 1)$$

For 64 processors, each PE needs 14 SLMs.

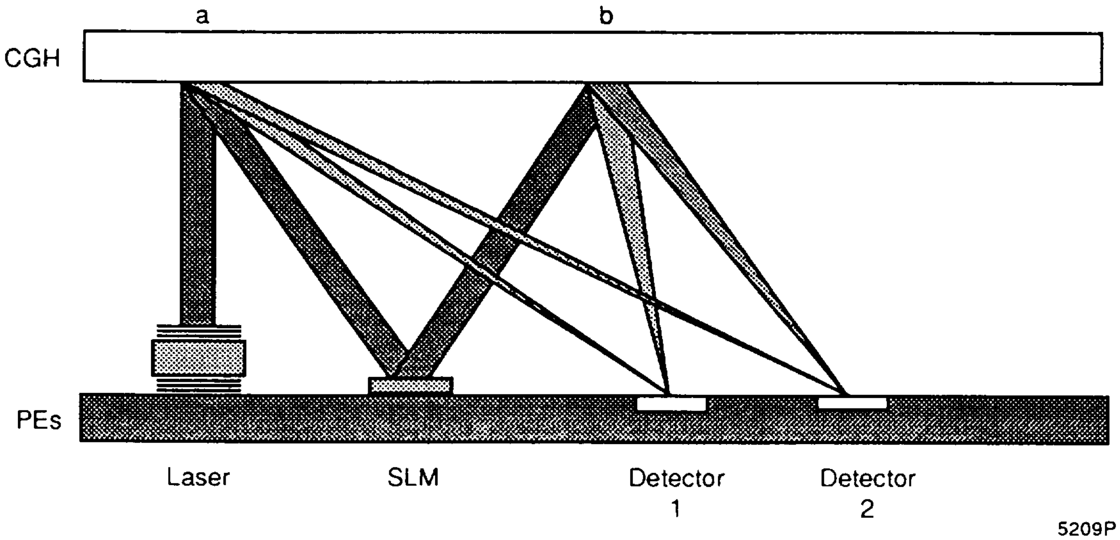

Figure 7. A basic concept of interconnection between two Pes.

Using phase modulators in beam forming and beam steering is an emerging field that is garnering attention.[18] Figure 8 demonstrates a method using phase modulated micromirrors to produce necessary beam shape and direction. Also, the phase modulator can be used in a holographic data storage system as a phase-encoded reference beam.[19]

Figure 9 illustrates the scheme of writing to and reading from a photorefractive medium. The input data beam interferes with the phase-encoded beam and is recorded at one plane of the photorefractive material. By adjusting the optics, another array of data can be stored at another plane. Using an array of the photorefractive fibers, we can expect a storage density up to 10^{13} bit cm^{-3}.

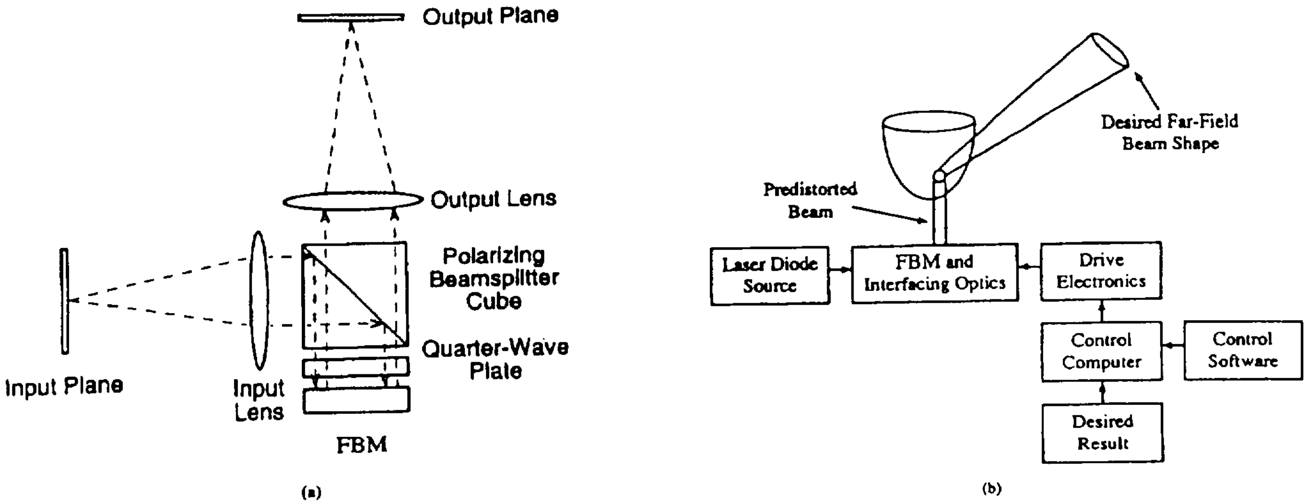

Figure 8. Active diffractive optics: (ā) General subsystem for beam shaping, aberration control, and optical interconnection. (b) Example system for optical antenna aberration correction.

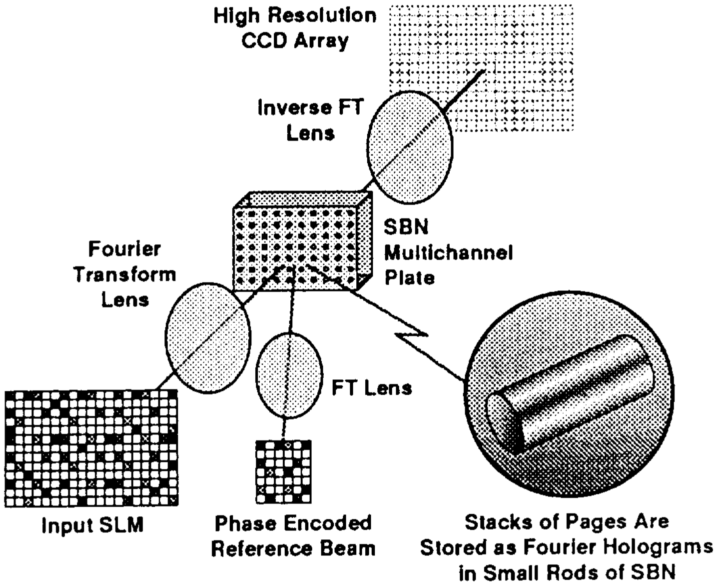

Figure 9. Schematic of holographic data storage system using binary amplitude SLM as data input, phase SLM as phase-encoded reference beam, SBN as holographic storage medium, and CCD as readout device.

IV. MEMBRANE DEVICES FOR INTEGRATED OPTIC APPLICATIONS

Photonic ON/OFF and routing switches can be made using alterations of the modal effective index caused by changing the cladding on a dielectric waveguide. Drumhead-like aluminum membranes are formed suspended over passive waveguides. The membranes are electrostatically pulled into contact with the waveguides, with operating times of tens to hundreds of microseconds. A routing switch can be made using the change in the real part of the modal index, as shown schematically in Figure 10. A directional coupler is fabricated in the waveguide layer to have a coupling ratio of unity; i.e., all the light is coupled from the input to the "cross" channel when the membrane is undeflected. Another way of saying this is that the air-clad directional coupler is made exactly one coupling length long. When a membrane is pulled into contact with the cross-channel waveguide, the effective index of that channel changes so as to destroy the synchronism of the coupler. If the index change is sufficiently large, negligible cross-coupling occurs, and all the light remains in the "bar" output channel. Although the synchronism could be altered sufficiently to cause switching by deflecting a membrane over either of the coupled guides, it is preferable to pull the cross-channel membrane down so that any losses caused by the absorption of the metal film will occur in the cross channel, thus enhancing the crosstalk performance in the bar state. A simple 2-D beam propagation method (BPM) model has shown that complete switching is obtained for the index changes available in this system, even with an air gap of 0.1 μm under the membrane.

Figure 11 shows the membrane Mach-Zehnder interferometer optical switch. It consists of two 3 dB couplers connected by two equal-length straight waveguides. An aluminum membrane suspended a few micrometers above one of the two interferometer arms acts as a phase shifter. The input optical light is divided into two equal components by the first 3 dB coupler. One of the two components is then modulated in phase by the effect of an aluminum membrane. With the membrane up, the two wave components experience an identical phase shift; the optical power crosses over and leaves through the "cross" output channel. As the metal membrane is electrostatically pulled into contact with one of the two arms of the interferometer, the effective refractive index of the guided mode in that arm changes. If the index change is sufficiently large to introduce a π phase shift difference between the two wave components, all the optical power will go straight across, emerging from the "bar" output channel.

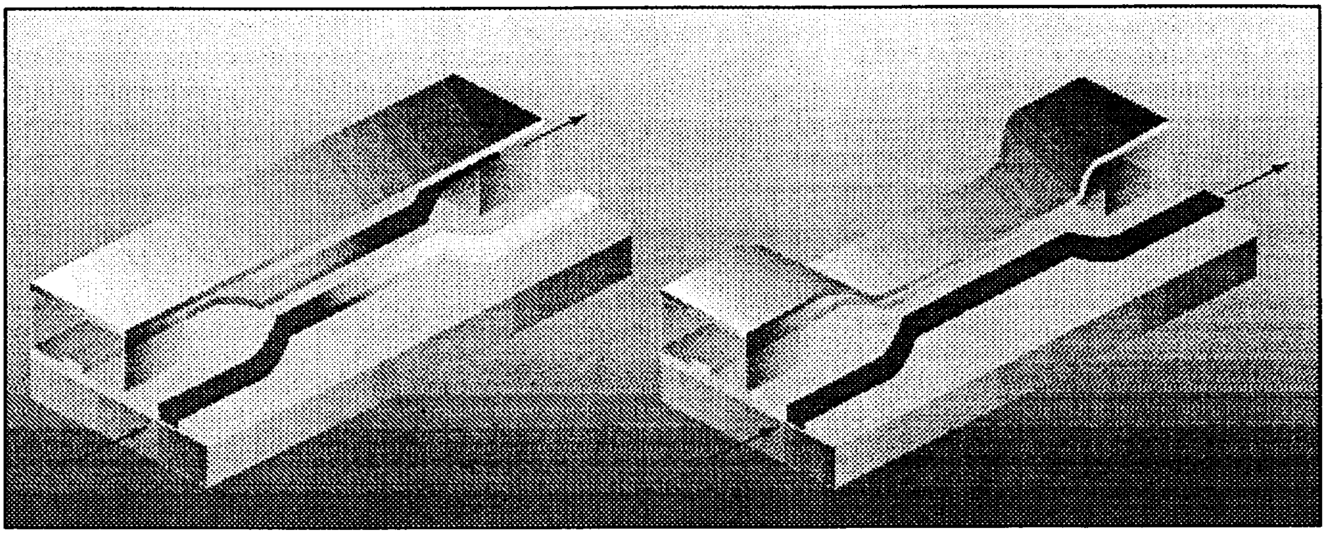

Figure 10. Routing switch based on a directional coupler. (a) Membrane undeflected: output directed to cross channel by the directional coupler; (b) Membrane deflected to touch cross channel: coupler unbalanced, light remains in the bar channel.

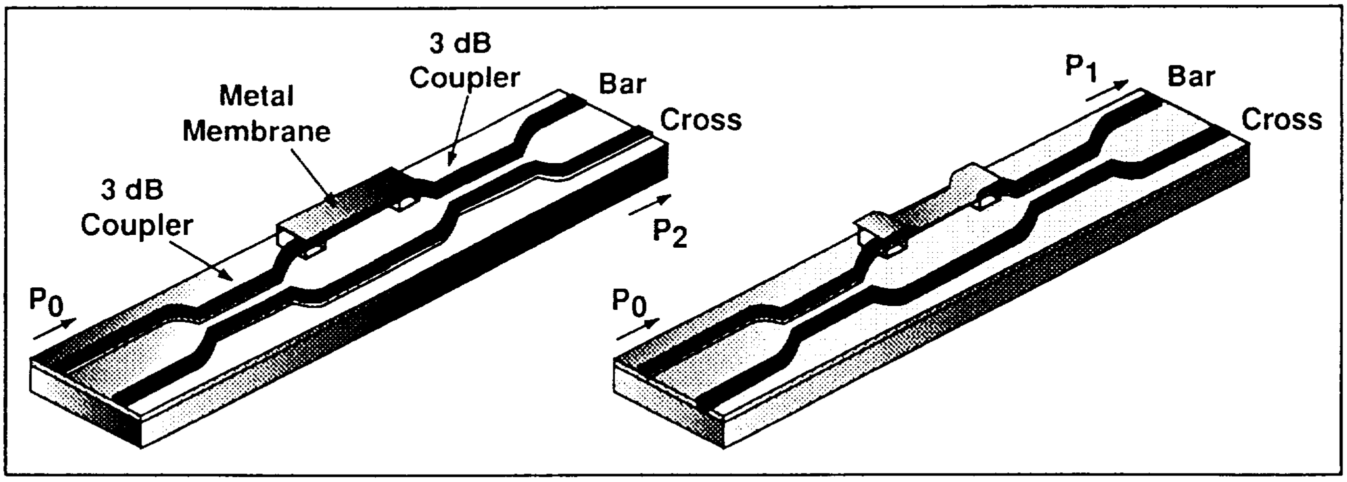

Figure 11. Metal membrane optical switch based on a Mach-Zehnder interferometer: (a) membrane up, (b) membrane down. Membrane may be placed over either channel in the center region of the switch.

V. DRUMHEAD DEVICE FOR RF APPLICATIONS

The first micromechanical switch was introduced in 1979.[20] However, micromechanical switches were not intensively considered for system applications until the early 1990s.[21-24] Surface micromachining and batch process technology became more mature and cost-effective, which made the device more attractive. TI investigated intensively in the early 1990s also, and obtained encouraging results.[24] Our switching elements are all based on the same metal membrane material as TI's micromirrors. The membranes are actuated by dc potentials to make or break the path of RF or microwave signals. By selecting proper materials and dimensions for the membrane and electrodes, the switches can be used to switch the signals at reasonable switching voltages.

From a functional point of view, the micromachined switches can be divided into resistive and capacitive switches (Figure 12). Our resistive switch yielded 1.5 to 2.5 ohms of dc resistance. For our long-term goals, capacitive switches are simpler and use lower voltage and power for switching because they do not need to recess the actuating electrodes, and a larger percentage of voltage and power for electrostatic actuation. The first capacitive switch (Figure 13) shows switching action in capacitive RF reflection measurement.

The compatibility of membrane switch construction with silicon CMOS processing makes this RF switch an attractive candidate for microwave integration with other passive RF devices. Low-cost microwave phase shifters can be fabricated using this technology and incorporated on the same substrate with other active or passive components.

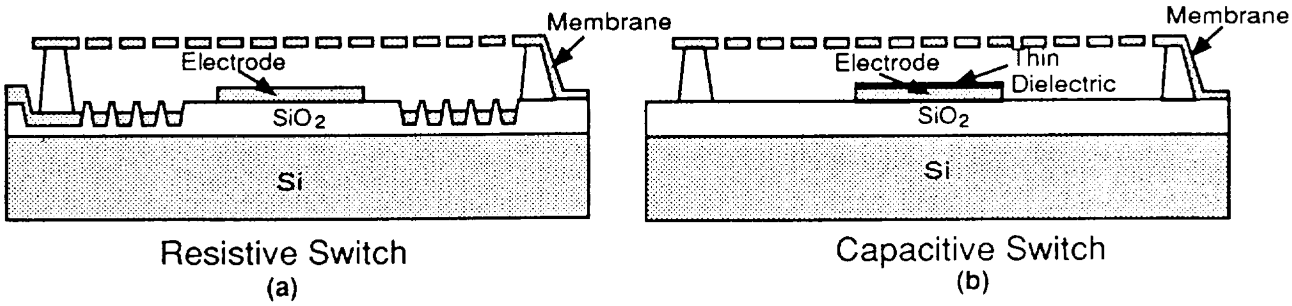

Figure 12. Cross-sectional view of (a) resistive RF switch and (b) capacitive RF switch.

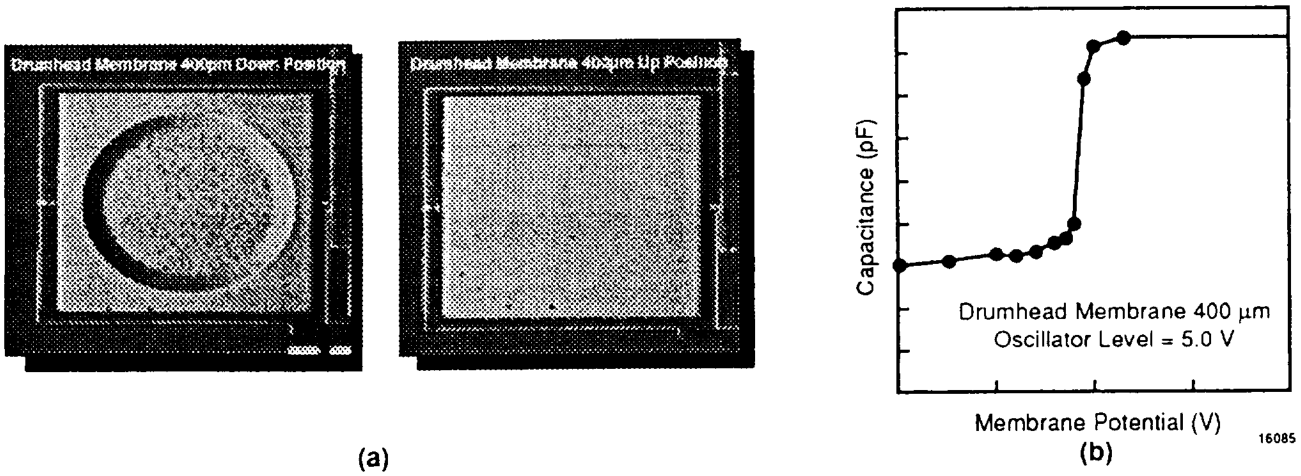

Figure 13. (a) Drumhead capacitive switch at down ("on") state and up ("off") state. (b) Result of the capacitance change versus actuation voltages.

VI. COMPUTER-AIDED DESIGN

Fabrication equipment and processes are very expensive. To minimize trial-and-error or major mistakes, computer-aided design (CAD) tools have been widely used in many industries (e.g., SPICE and SUPREM for semiconductors and ABAQUS for mechanical design). Micromachining is in its infancy, but demands for understanding of electromechanical and magnetomechanical micromechanisms are growing rapidly. Simulation tools were developed at different institutes based on specialized needs. For general-purpose micromachining, MIT's MEMCAD[25] and the University of Michigan's CAEMEMS[26] are the best known CAD tools. TI became one of the first two industrial beta sites[27] for MIT's MEMCAD. TI also worked closely with MIT to design test structures to characterize and monitor material properties such as Young's modulus, stress, and Poisson ratio. These parameters can then be used in both micromechanical simulation and process control monitoring. (We have obtained some preliminary results but they are inconclusive.) Design and process revision are under development. Figure 14 shows the MEMCAD is capable of taking a layout directly and converting it into a mechanical structure through process description file. MEMCAD can then mesh the structure and use finite element methods to simulate mechanical behavior of the device.

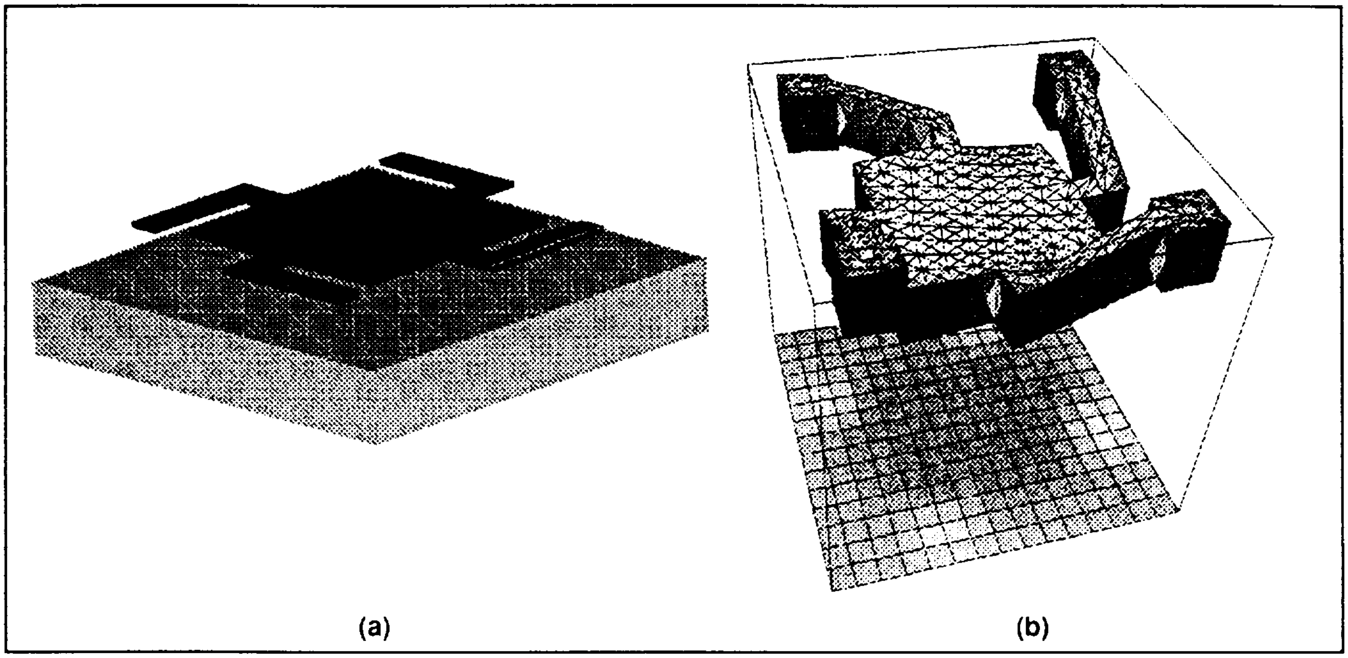

Figure 14. (a) 3-D graphical structure of a flexure-beam micromirror converted from layout and process description file. (b) Finite element method and electromechanical simulation of the micromirror in MEMCAD.

VII. SUMMARY

TI has developed IC process compatible micromechanical devices for more than 15 years. Some devices were successfully transferred to productization, while many opportunities remain to be explored. We covered in this paper: (1) the development of high-performance fiber-optic crossbar switches from optical table version to integrated packaging version; (2) new flexure-beam micromirror phase modulators and applications for image processing, optical interconnect, beam forming, and holographic data storage; (3) membrane devices for integrated-optic application by using the contact of membrane to the waveguide to change the effective refractive index; (4) RF switch as the only electrical application that can impact the telecommunication technology through its favorable performance and cost effectiveness; and (5) collaboration with MIT to boost our simulation capability using MEMCAD. We expect the micromirror/membrane technology to be an important technology in the 21st century. Opportunity and applications are waiting for development.

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