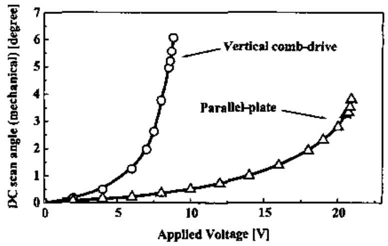

TuO3 **Fig. 3.** Measured DC scanning characteristics of the micromirror with vertical comb-drive actuator (circle) and with parallel-plate actuator (triangle).

Fig. 3 shows the measured result. The mirror is tilted by 6° (mechanical angle) with 9 V bias. The total optical scan angle is 24°. Good uniformity (±5%) across the array is obtained. For comparison, a parallel-plate-actuated micromirror with the same mirror size, spring dimension, and mirror height was also fabricated on the same wafer. The scanning characteristic is shown in Fig. 3 as well. It has smaller scan angle (3.8°) and much higher operating voltage (21 V).

3. WDM Routers

The WDM router in Fig. 1(a) is currently under test. The current system employs a two-inch lens with a focal length of 150 mm and a grating of 600 lines/mm. This initial system can accommodate 6 spatial channels and 10 wavelength channels. The calculated beam waist on micromirror (ω_{mirror}) is 36 μm with the beam waist of collimator (ω_{col}) of 2 mm. The performance of the system was analyzed by using Gaussian beams and ZEMAX. The optical insertion loss of the system is estimated to be less than 1.5 dB, with less than 0.3 dB variations across the spatial channels and less than 0.1 dB variations across all wavelength channels. Larger number of spatial and wavelength channels can be achieved by employing 2-D arrays of spatial channels and 2-axis scanning micromirror arrays.

4. Conclusion

A MEMS micromirror array with hidden vertical comb-drive actuator and springs has been successfully demonstrated. The devices were fabricated using SUMMiT-V process. The fabricated micromirror showed large optical scan angle (24°) and low actuation voltage (9 V). The fill-factor of the micromirror array was as high as 91%. Applications of the micromirror array for WDM routers are also discussed.

References

1. J.E. Ford, V.A. Aksyuk, David J. Bishop, and J.A. Walker, "Wavelength add-drop switching using tilting micromirrors," J. Light. Technol., 17, 904–911 (1999).
2. A. Husain, "MEMS-based photonic switching in communications networks," in OFC 2001, Paper WX1.
3. R. Ryf, et al., "1296-port MEMS Transparent Optical Crossconnect with 2.07 Petabit/s Switch Capacity," in OFC 2001, Postdeadline Paper PD28.
4. J.S. Patel and Y. Silberberg "Liquid crystal and grating-based multiple-wavelength cross-connect switch," IEEE Photon. Technol. Lett., 7, 514–516 (1995).
5. S. Miller, K. Turner, and N. Macdonald, "Microelectromechanical scanning probe instruments for array architectures," Rev. Sci. Instrum., 68, 4155–4162 (1997).
6. J.-L.A. Yeh, H. Jiang, and N.C. Tien, "Integrated polysilicon and DRIE bulk silicon micromachining for an electrostatic torsional actuator," J. Microelectromech. Syst., 8, 456–465 (1999).

TuO4 **3:00 pm**

Digital MEMS switch for planar photonic crossconnects

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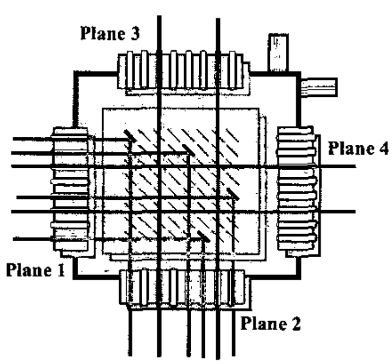
1. Introduction: Planar optical crossconnects

Optical switches are data rate and protocol independent, which makes them attractive for optical networks.[1-3] Free-space optical switches offer low loss, PDL, and cross-talk. MEMS-based approaches to miniaturize opto-mechanical switches have been proposed. They offer scalability combined with excellent optical performance. Arranging mirrors on a silicon substrate various switching functions can be performed. A functional diagram of a two-dimensional (2-D) 8 × 8 switch are shown in Figure 1. If the micro-mirrors are turned on, the light signals from Plane 1 can be directed to outputs in Plane 2. When the mirrors are off, then the light from Plane 1 can pass through to outputs in Plane 4. This architecture is called 2D because it uses N^2 individual mirrors and switch cells, e.g., 256 devices for a 16 × 16 switch. The main elements of the MEMS switch cell are the mirror and the actuator. The mechanical design of the switch cell determines the optical characteristics of the component.

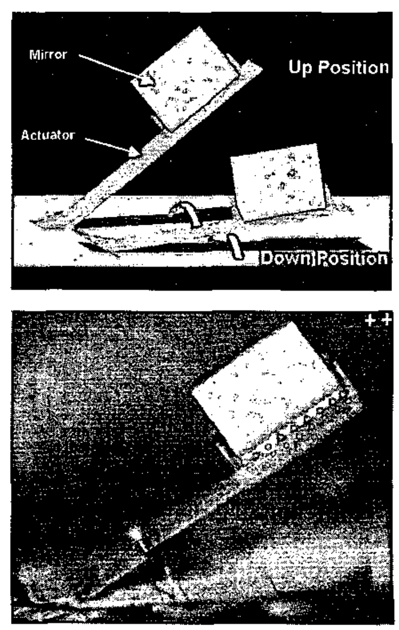
2. Design of a digital MEMS switch

For fiber-optical switches, the challenges are how to obtain large travel distance, high accuracy and repeatable angle as well as fast switching speed at the same time. Especially for large array such as 16 × 16, the collimator beam waist could be larger than 100 μm. The actuator design needs to be able to provide repeatable traveling distance more than several hundred microns in order to completely switch the mirrors on and off. Comb drives have been proven to be reliable actuators. However, it would be difficult to actuate long distance with small footprint by surface micro-machine process. Thermal actuators and scratch drive actuators are not considered because of long-term reliability and repeatability issues. Piezoelectric actuation requires the use of materials with high piezoelectric effect, such as zinc oxide or lead-zirconate-tintanate (PZT), which are not readily compatible with IC fabrication techniques. Magnetic actuation can generate very large forces, but the effects are difficult to shield, making it difficult to make large arrays of independent actuators. Magnetic actuators also dissipate power near the MEMS devices. Gap-closing electrostatic actuator exploit the attraction of oppositely charged mechanical elements, and is considered one of the best candidates for actuation. Its advantages include repeatability, low power consumption and ease of shielding. It also does not require special materials.

Figure 2a shows the schematic diagram of the basic switch elements. Figure 2b photograph shows the detail structures of the mirror, actuator and the landing stopper. The gap-closing actuator plate initial angle is assembled and actuated by electro-static force from the electrodes. The mirror is assembled at 90 degrees and sits on the actuator plate. Large traveling distance is achieved by extending the actuator arm. The extended arm doesn't generate much more force. However, several hundred microns displacement can be achieved with this configuration. The switching is achieved by moving the actuator up and down. The mirror is maintained to be 90 degrees during the entire switching cycle. The mirror traveling direction is perpendicular to the optical path. This design has advantage over the pop-up mirror configuration, which rotate the mirror from



TuO4 **Fig. 1.** Switching architecture.



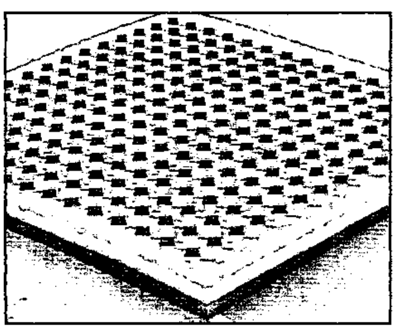
TuO4 **Fig. 2.** a). Schematic diagram of 2D MEMS switch. b). Photograph of single digital switch.

zero to 90 degrees. The insertion loss would be very sensitive to the mirror final (actuated) angle.

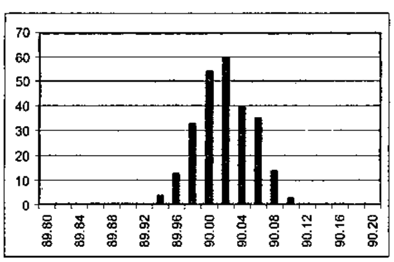
In order to stop the mirror and prevent electrical shorting, a special stopper is designed and positioned above the electrode. Because of the tilting angle from actuator and the bending of the stopper, the actuator will only contact the corner of the landing bar with a single point of contact. This is the key element to ensure high reliability and prevent stiction problems. It also helps to settle the mirror ringing and improve the switch time. The device can be driven by a square wave voltage function without pre-shaping waveform and still achieve 12 ms switching time. More than 100 million cycles have been demonstrated with repeatable mirror angle and performance. The actuator is moving in the air and not in contact with substrate except the single point contact of the final landing. It is different than sliding the mirror back and forth, which would make continuous mechanical contact with the surface.

3. Test Results

Figure 3 shows a SEM of 16 × 16 on single chip. Figure 4 shows the angle uniformity of <±0.1 degrees achieved with this technology. Collimators have been aligned to this chip and the component has been hermetically sealed before measuring performance parameters. For switches manufactured with this technology, the specified maximum insertion loss for a 16 × 16 is less than 6 dB for all states and cross-talk <–50 dB. Variation of loss over the entire 1280–1650 nm range is <1 dB. Return loss is >50 dB, and maximum temperature variation is <1 dB over a temperature range of 0–60 degrees C. Polarization Dependent Loss (PDL) is <0.4 dB and Polarization Mode Dispersion (PMD) is <0.08 ps. Maximum switch time is 12 ms. In fact, specific 16 × 16 switches have been manufactured with maximum insertion loss under 3.1 dB. Vibration tests showed <0.2 dB change under operation, and 3 axis shock tests confirm no change of operational characteristics under 200 G.



TuO4 Fig. 3. SEM of 16 × 16 array of 2D MEMS switch.



TuO4 Fig. 4. Angle histogram of mirror angles for typical 16 × 16 switch mirror.

4. Summary

In conclusion we have demonstrated fully non-blocking 16 × 16 switches in a single chip solution using MEMS fabricated by a surface micro-machining. We have shown how the critical mechanical elements of the MEMS-cell have been chosen to achieve large mechanical movement, high angular repeatability of the movement, and high reliability of the actuation mechanism, which translated into low loss and high reliability of the packaged component. Test results for these components have been presented.

References

1. H. Toshiyoshi, et al., J. MEMS, vol. 5, no. 4, pp. 231–237, 1996.
2. L.Y. Lin, et al., IEEE PTL, vol. 10, no. 4, pp. 525–527, 1998.
3. IEEE: A.Q. Liu, et al., LEOS, pp. 37–38, 2000.

TuO5 3:15 pm

Nano-Electro-Mechanical Photonic Crystal Switch

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1. Introduction

Photonic crystals (PCs) have the ability to confine light propagation within small volumes for specific frequency ranges, known as photonic bandgaps (PBG). Furthermore, by inserting defects in the host PBG structure, we can engineer high quality factors and narrow bandpass transmission spectra in the photonic bandgap. Due to these properties, many practical implement actions such as planar photonic crystal waveguides,[1–3] polarizers, optical filters,[4] optical switches and PBG defect mode lasers[5] were engineered. Potentially, integration of these passive and active elements can form complex optical circuits on a chip.

MEMS-based optical switches have been developed for optical networks in recent years, due to their capability to reduce insertion loss, crosstalk and power consumption.[6] A wide variety of device designs have been realized. Most switches either use micromirrors to change light path between input/output channels or directly move the waveguides or fibers for channel coupling.[7] In this paper, we demonstrate a 1 × 1 optical switch using an integrated photonic crystal with MEMS actuators.

2. Device Design

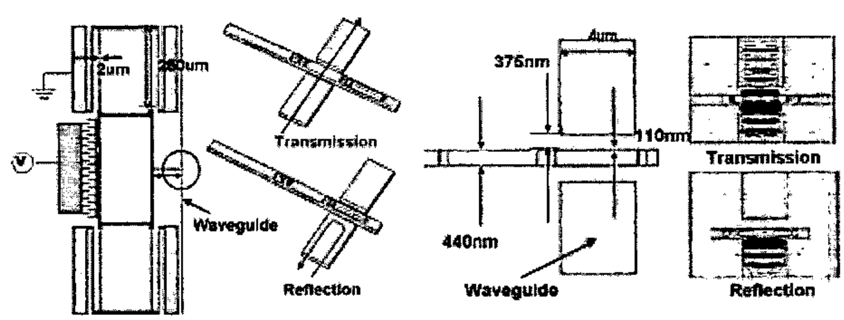
Photonic crystals can be classified as 1D, 2D, and even 3D structures, depending on how many dimensions the PC confines light. However, high dimension PC structures are still difficult to fabricate and are not easily integrated with actuators. In our design, an input and output Si waveguide are optically linked by a 1D PBG active component. We designed two separate PC structures: 1) a reflection state that serves as a broadband notch filter centered at 1.55 μm and extending from 1.0 μm to 2.1 μm 2) a transmission state with the same notch filter properties, however allowing a narrow bandpass at 1.55 μm. Connected to a MEMS actuator, the active component can be switched between either one of these structures. This allows us to control the flow of light as it passes along the waveguide. The whole structure is shown in Fig. 1a.

The reflection structure's silicon feature and air gaps were designed at quarter-wavelength thickness (from a 1.55 μm center wavelength). The transmission structure's silicon feature was designed at a full-wavelength thickness, allowing the peak transmittance located at the 1.55 μm center wavelength.[8]

The silicon was the material for the photonic crystal because of its high refractive index that enhances the Q of the filtering with only a few periods in compact periodic structure. The reflection state's silicon feature and air gaps were designed at quarter-wavelength thickness (from a 1.55 μm center wavelength). The transmission state's silicon feature was designed at a full-wavelength thickness, allowing the peak transmittance located at the 1.55 μm center wavelength.[8] The more detail dimension is shown in Fig. 1b.

2. Fabrication

The whole device was fabricated on a Silicon-On-Insulator (SOI) wafer. The thickness of device layer is 1.5 μm and the silicon dioxide layer is 0.5 μm. SOI was chosen due to its flat, monocrystalline surface and low residual stress of single crystal, which is more reliable for the nanofabrication. First, we grow 100 nm thermal oxide on the top of device. Then E-beam lithography and optical lithography was used to pattern structures. E-beam lithography combined with



TuO5 Fig. 1. (a). Nano-Electro-Mechanical photonic crystal switch. The left hand part is the actuator. The right hand part is the 1D PBG active component with two different switch states. (b). Detail dimension of the optical component. The right hand part is FDTD simulation for different two state.