A High-Speed Low-Voltage Stress-Induced Micromachined 2 × 2 Optical Switch

R. T. Chen, *Student Member, IEEE*, H. Nguyen, *Student Member, IEEE*, M. C. Wu, *Member, IEEE*

***Abstract*—A low-voltage electrostatically actuated 2 × 2 fiber optic switch is achieved using a stress-induced curved polysilicon actuator. The curved polysilicon beam substantially lowers the electrostatic operating voltage of the switch. Large mirror displacement (300 μm) and low operating voltage (20 V) are obtained simultaneously. Sub-millisecond switching time (<600 μs), low optical insertion loss (0.7 dB), and small polarization-dependent loss (0.09 dB) have been achieved.**

***Index Terms*—MEMS, micromachined fiber optic switch, optical switch, stress.**

I. Introduction

The RAPID growth of fiber optic networks has stimulated a great interest in optical switching. Optical switches with low optical insertion loss and crosstalk are needed for protection, restoration, and reprovisioning of the networks. Optical crossconnect with a large port count is particularly interesting. Optomechanical switches are preferred for these applications because they have very low optical insertion loss and crosstalk. In addition, they are independent of wavelength, polarization, bit rate, and modulation format. Unfortunately, conventional optomechanical switches are bulky, slow, expensive, and often unreliable. Recently, there has been a great deal of interest in compact and lightweight optomechanical switches realized by microelectromechanical systems (MEMS) technology [1]–[6]. The MEMS-based switches are inherently fast and have low power consumption. They are manufactured by batch fabrication processes and can be mass-produced at low cost. More importantly, MEMS technology enables large matrix switches to be monolithically integrated on a single chip.

Collimated optical beams are usually employed in free-space MEMS optical switches with large port count. Large mirrors and mirror displacement are desired to ensure low insertion loss and low crosstalk. However, most of the reported switches with large mirror displacements suffer from high switching voltages. A low operating voltage will allow the switch to be directly driven by standard CMOS integrated circuits. In this letter, we report on a novel MEMS fiber optic switch with low operating voltage and large mirror displacement. A 2 × 2 optical switch with operating voltage of 20 V, switching time of 600 μs, and optical insertion loss of 0.7 dB for single-mode fibers (SMF's) has been demonstrated. The switch reported here can be arrayed to form a large matrix switch [2].

Manuscript received May 24, 1999; revised July 30, 1999. This work was supported in part by the Defense Advanced Research Projects Agency (DARPA).

The authors are with the Electrical Engineering Department, University of California at Los Angeles, Los Angeles, CA 90095-1594 USA.

Publisher Item Identifier S 1041-1135(99)08700-5.

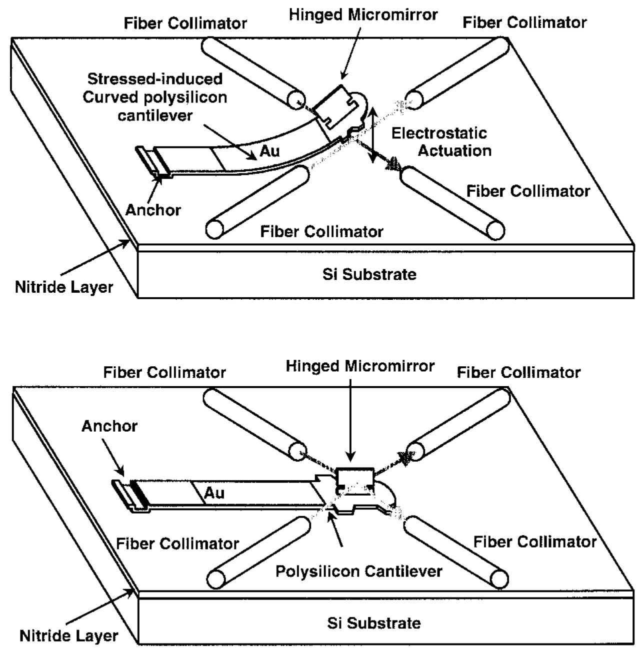


Fig. 1. Schematic of the low-voltage MEMS fiber optic switch realized by stress-induced bending of a polysilicon cantilever beam.

II. Design and Fabrication

The operating principle and a schematic drawing of the 2 × 2 switch are illustrated in Fig. 1. The optical switch consists of an elevated vertical micromirror (300 × 175 μm^2) that can be lowered to reflect the optical beams. The micromirror is located in the center of four single mode fiber collimators in a cross configuration. A gold-coated micromirror is attached to the end of a polysilicon cantilever beam using microhinges and microspring latches. A stressed layer of Cr–Au is deposited on the cantilever beam to raise the mirror above the path of the optical signal. The cantilever beam curves upwards because the polysilicon is under compressive residual stress while the Cr–Au film is under tensile residual stress. To actuate the switch, a voltage is applied between the cantilever and the substrate. Electrostatic force lowers the mirror from the cross (transmission) state to the parallel (reflection) state. The curvature of the beam allows a large mirror displacement while maintaining a small initial gap between the cantilever beam and the lower electrode (substrate). This design significantly

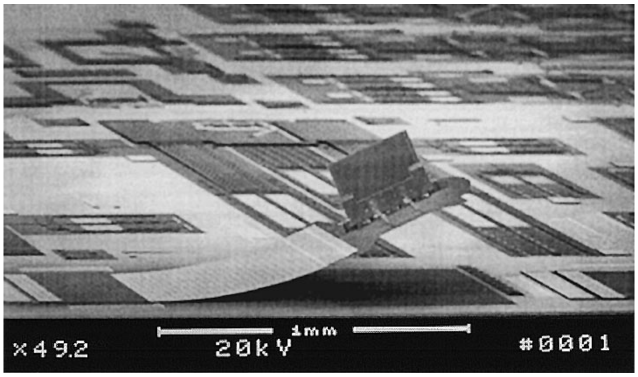


Fig. 2. SEM of optical switch.

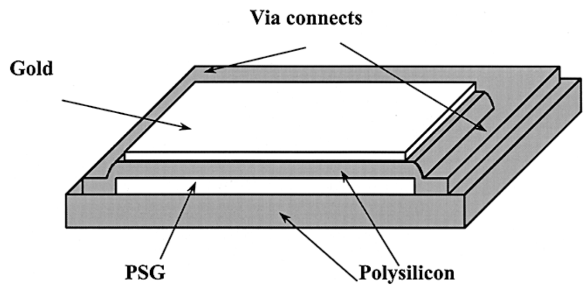


Fig. 3. Cross section of micromirror.

reduces the voltage necessary to pull down the cantilever beam [7]. A similar actuator using Cr–Al has been reported in [8].

The optical switch is fabricated at the MEMS Technology Application Center at North Carolina (MCNC) using the Multiuser MEMS Processes (MUMP's). The 1.5-μm-thick polysilicon cantilever beam is fabricated on a sacrificial layer of phosophosilicate glass (PSG). A 20-nm-thick Cr and a 0.5-μm-thick Au film are deposited on the cantilever to induce the internal stresses. Upon releasing in hydroflouric (HF) acid, the cantilever arm curves upward, which raises the mirror off the substrate. The total length of the cantilever is 1.5 mm, of which 730 μm is curved. Fig. 2 shows a scanning electron micrograph (SEM) of the micromachined optical switch. The tip of the cantilever has been raised by 300 μm above the substrate. The switch is isolated from the substrate with a 0.5-μm film of silicon nitride.

The metal used for coating the mirror is deposited concurrently with the metal used to induce the stress in the curved cantilever beam. Therefore, the stress in the metal will also cause the mirror to warp, increasing the insertion loss. To prevent the mirror from warping, a three layer polysilicon-PSG-polysilicon stack with a total thickness of 4.25 μm is used to keep the mirror rigid. The PSG is trapped and sealed between the two polysilicon layers to protect it from being etched in the releasing step. A cross section of the mirror is shown in Fig. 3.

III. RESULTS

The switch is actuated by applying a voltage between the polysilicon cantilever beam and the substrate. The tip of the cantilever gradually lowers until the pull-down voltage, at which the tip completely snap down to the substrate. The

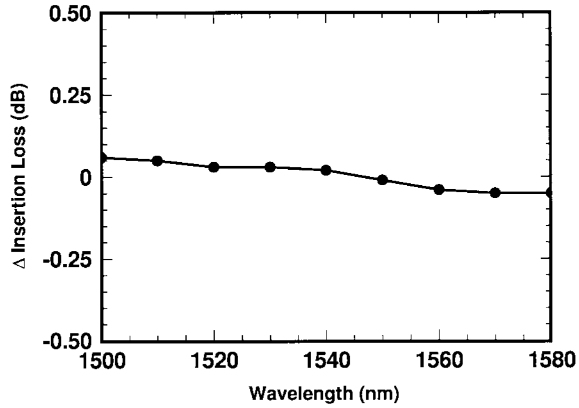


Fig. 4. Relative change (Δ) in insertion loss versus wavelength from 1550 nm.

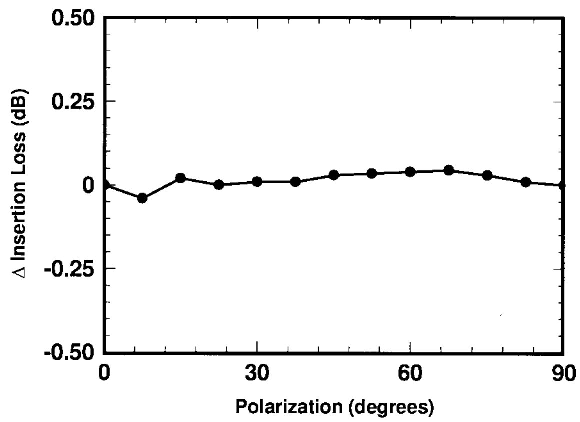
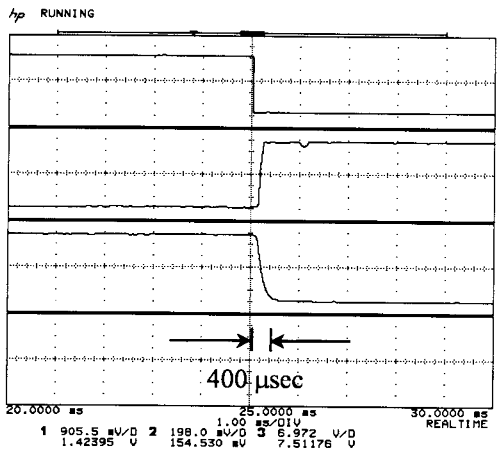
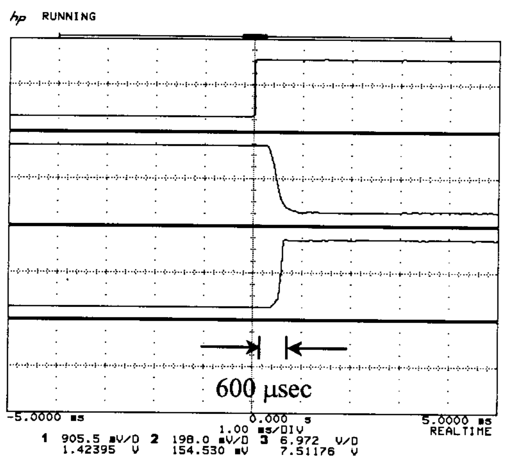


Fig. 5. Relative change (Δ) in insertion loss versus polarization from 0°.

bistability is typical of gap-closing type electrostatic actuators. The pull-down voltage is measured to be 20 V. The optical insertion loss was measured using a pair of commercial (Namiki) single-mode fiber collimators with ball lens attached to the fiber. The collimators are anti-reflection (AR) coated at 1550 nm, and are mounted on five-axis alignment stages with 0.1-μm accuracy. The micromirror (300 × 175 μm) has a total vertical movement of 306 μm, allowing complete coverage of the collimated beam (50 μm diameter). The optical insertion losses for the single mode fibers were 0.55 dB in the cross state (collimator to collimator) and 0.7 dB in the parallel state. Both states had negligible crosstalk (< -80 dB). These measurements include the loss of one additional fiber connector. Mirrors that were not fabricated using the poly/PSG/poly stack had an insertion loss of 2.7 dB. An external cavity tunable semiconductor laser with a tuning range of 1500–1580 nm was used as the optical source to measure the wavelength dependence of the optical switch. The measured insertion loss (relative to 1550 nm) versus the wavelength is shown in Fig. 4. There is a small wavelength-dependent loss (0.12 dB) caused by the fiber collimators. The reflectivity of the gold-coated micromirror is relatively flat across the measurement range. The polarization-dependent loss of the switch is also measured using the same setup. As shown in Fig. 5, the insertion loss remains relatively unchanged (<0.09 dB) when the polarization is varied from 0° to 90°.



(a)



(b)

Fig. 6. The dynamic response of the switch. (a) Rise time. (b) Fall time. The top, middle, and bottom traces are input, cross-state signal, and parallel-state signal, respectively.

The dynamic response of the switch was measured using a HP834 440D photodetector. A square wave with peak voltage of 20 V was applied to the cantilever beam. The dynamic response is shown in Fig. 6. The fall time, corresponding to the snap-down of the switch, was 600 μs. The rise time, corresponding to the release of the switch, was 400 μs.

IV. Conclusion

We have reported a novel silicon surface micromachined 2×2 optical switch for telecommunication applications. A relatively low switching voltage (20 V) was achieved using a stress-induced curved actuator. The mirror was displaced by 300 μm during switching to ensure full coverage of collimated beams. The switching times were 400 and 600 μm for the rise and fall times, respectively. The insertion losses for single mode fibers were 0.55 dB for the cross state and 0.7 dB for the parallel state. The optical switch had very low wavelength dependence ($<$0.12 dB) and polarization dependence ($<$0.09 dB).

Acknowledgment

The authors would like to thank Dr. L. Fan for helpful discussions, T. Jung for help with the optical measurements, and J. Su for taking the SEM pictures.

References

[1] H. Togo, M. Sato, and F. Shimokawa, "Multi-element thermo-capillary optical switch and sub-nanometer oil injection for its fabrication," in *Proc. IEEE Micro Electro Mechanical Systems*, Jan. 1999, pp. 419–423.

[2] L. Y. Lin, E. L. Goldstein, J. M. Simmons, and R. W. Tkach, "High-density micromachined polygon optical crossconnects exploiting network connection-symmetry," *IEEE Photon. Technol. Lett.*, vol. 10, pp. 1425–1427, Oct. 1998.

[3] M. Mita, D. Miyauchi, H. Toshiyoshi, and H. Fujita, "An out-of-plane polysilicon actuator with a smooth vertical mirror for optical switch applications," in *IEEE LEOS Summer Topical Meetings*, 1998, pp. 33–34.

[4] C. Marxer, M.-A. Gretillat, N. F. de Rooij, R. Battig, O. Anthamatten, B. Valk, and P. Vogel, "Vertical mirrors fabricated by reactive ion etching for fiber optical switching applications," in *Proc. 10th Workshop on Micro Electro Mechanical Systems (MEMS)*, 1997, pp. 49–54.

[5] S. S. Lee, L. S. Huang, C. J. Kim, and M. C. Wu, "2 × 2 MEMS fiber optic switches with silicon sub-mount for low-cost packaging," in *Solid-State Sensor and Actuator Workshop Hilton Head Island, SC*, 1998, pp. 281–284.

[6] V. Aksyuk, B. Barber, C. R. Giles, R. Ruel, L. Stulz, and D. Bishop, "Low insertion loss packaged and fiber-connectorized Si surface-micromachined reflective optical switch," in *Proc. Solid-State Sensor and Actuator Workshop Hilton Head Island, SC*, 1998, pp. 79–82.

[7] R. Legtenberg, E. Berenschot, M. Elwenspoek, and J. Fluitman, "Electrostatic curved electrode actuators," in *Proc. IEEE Micro Electro Mechanical Systems*, 1995, pp. 37–42.

[8] T. Yasuda, I Shimoyama, and H. Miura, "CMOS drivable electrostatic microactuator with large deflection," in *Proc. IEEE 10th Annu. Int. Workshop Micro Electro Mechanical Systems*, 1997, pp. 90–95.