Development of a Large-scale 3D MEMS Optical Switch Module

Tsuyoshi Yamamoto†, Johji Yamaguchi, Renshi Sawada, and Yuji Uenishi

Abstract

A three-dimensional (3D) micro-electro-mechanical system (MEMS) optical switch, consisting of two-axis tilt mirror arrays and free-space optics, is a practical solution for constructing large-scale switching fabrics due to its high component density and low cost. The MEMS-mirror arrays developed by NTT are single-crystal silicon mirrors integrated with high-aspect ratio torsion springs and actuated by electrostatic forces. The free-space optics consist of low-cost high-precision polymer components assembled passively. A prototype module with 100-channel optical fiber input/output exhibited a low coupling loss of 4.0 dB and a switching time of 3 ms.

1. Introduction

The rapid growth of broadband network services is a driving force behind the development of the next-generation optical network based on dense wavelength division multiplexing. From the viewpoint of resource management in the network, wavelength-path-level optical cross-connects (OXCs) are mission critical technologies due to their multiple restoration capabilities. These enable features like high robustness against traffic fluctuations and an optimum network configuration in the most cost-effective manner; they are made possible by dynamically allocating network resources [1]. Recent progress in optical switches systems based on micro-electro-mechanical system (MEMS) devices should lead to the construction of a large-scale, all-optical switch for practical OXCs [2]-[3].

NTT Microsystem Integration Laboratories has been developing large-scale three-dimensional (3D) MEMS optical switches that are compact and inexpensive. The main components of the switch are MEMS two-axis tilt mirror arrays and free-space optics. The MEMS mirrors are made of single-crystal silicon with integrated gimbal structures and are tilted two dimensionally by electrostatic force. The free-space optics for internal connections of the switch consist of low-cost precision-made polymer components and are passively assembled using conventional dowel pins. We also present the results of a prototype having 100 input and 100 output ports, showing the optical characteristics for internal connection and the switching operation.

† NTT Microsystem Integration Laboratories
Atsugi-shi, 243-0198 Japan
E-mail: t-ymmt@aecl.ntt.co.jp

2. Basic switch structure

3D MEMS optical switches are suitable for compact, large-scale switching fabrics because they utilize spatial parallelism, which enables high-density, 3D interconnections. The ability of this architecture to achieve input- and output-port counts of over one thousand is the primary driver of the large-scale OXCs. In particular, these types of switches provide high application flexibility in network design because of low and uniform insertion loss with low wavelength dependency under various operating conditions. Furthermore, this switch exhibits minimal degradation of the optical signal-to-noise ratio, which is mainly caused by crosstalk, polarization dependent loss (PDL), and chromatic and polarization mode dispersions.

Figure 1 shows the basic configuration of the 3D

MEMS optical switch. The optical signals passing through the optical fibers at the input port are switched independently by the gimbal–mounted MEMS mirrors with two-axis tilt control and then focused onto the optical fibers at the output ports. In the switch, any connection between input and output fibers can be accomplished by controlling the tilt angle of each mirror. As a result, the switch can handle several channels of optical signals directly without costly optical-electrical or electrical-optical conversion.

2.1 MEMS two-axis tilt mirror array

The attributes of MEMS mirror arrays depend on whether the mirror is made of polysilicon or single-crystal silicon. Polysilicon mirrors are fabricated using mature-micromachining technology, but it is difficult to achieve reliable connections in the switch due to mirror deformation caused by inherent stress in the materials [4]. Single-crystal silicon mirrors provide reliable connections due to their durable mechanical structure [5].

Figure 2 shows a MEMS mirror consisting of two single-crystal silicon substrates. The substrates are processed independently by silicon bulk micromachining [6] and bonded together. Each mirror is supported by folded torsion springs in two orthogonal axes and tilted two-dimensionally by electrostatic force. The torsion spring has an aspect ratio of > 6, and this high-aspect-ratio spring features a strong bending capability relative to torsion and provides strong support for the mirror. The tilt angle of the mirror can be changed by controlling the applied voltage between the two substrates. In this mirror, the driving electrode has a three-dimensional terrace structure, and this effectively reduces the control voltage compared with a conventional MEMS mirror.

The appearance of a fabricated MEMS mirror is shown in Fig. 3(a). The mirror has a diameter of 600 μm and is integrated with the gimbal structures that provide freedom of tilt about two axes.

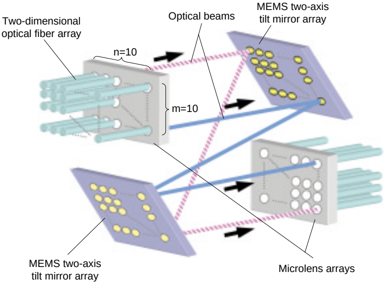


Fig. 1. Basic structure of 3D MEMS optical switch.

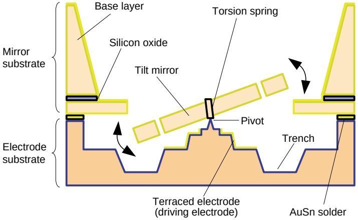
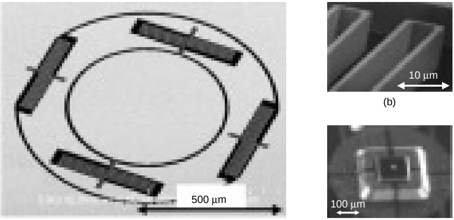


Fig. 2. Cross-sectional schematic of MEMS two-axis tilt mirror.

2.2 Low-cost, highly accurate optical components for free-space optics

The two-dimensional optical fiber and microlens arrays used to establish the internal connections of the switch determine the density, hardware volume, and cost of the switch. However, high-precision positioning is essential for assembling optical components that use two-dimensional array devices consisting of hundreds of small elements. Several assembly techniques have been reported [7]-[8], but such conventional assembly processes may be costly because they require highly accurate, time-consuming fiber handling.

To overcome these problems, a two-dimensional optical fiber array using single-mode optical fibers with metal micro–ferrules and a polymer substrate



(a) (b) (c)

Fig. 3. (a) MEMS mirror, (b) the high-aspect torsion spring, and (c) 3D terrace electrode with a pivot.

having precisely aligned holes was developed [9]. Figure 4 shows the configuration of the fiber array. Optical fibers with the metal micro–ferrules and two dowel pins are inserted into holes in the polymer substrate. Each ferrule end is polished and given an antireflection coating in advance. The polymer substrate with guide holes, made of a thermosetting molding compound, is molded using a transfer-molding method based on a common technique for fabricating ferrules in MT (mechanical transfer) -type optical connectors [10]. In this structure, the fiber arrays are passively assembled in a series of simple steps. The dowel pins are used for alignment between optical fiber and microlens arrays.

The optical fiber arrays in the switch module have a 10 × 10 arrangement. The fibers in each array are aligned with a 1.3-mm spacing with an average displacement of less than ±2 µm, which demonstrates that our two-dimensional optical fiber arrays provide high-precision fiber positioning. The microlens array is based on polymer that is transparent to wavelengths in the 1300–l600-nm range and is suitable for plastic-injection molding.

2.3 Optomechanics

The optomechanics in the switch generally require precise alignment with micrometer and sub-milliradian tolerance. The most critical positioning stability may be required between the fiber and the microlens arrays because a small misalignment between them will greatly increase the coupling loss. Therefore, the placement of each optical component must be kept stable over its lifetime with allowable errors measured in micrometers.

To overcome these problems, we used a passive assembly approach for constructing the optomechanics in the switch. Figure 5 shows a photograph of the

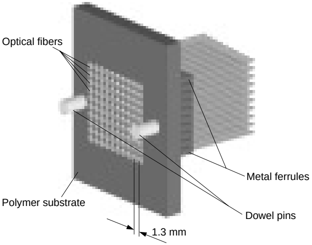


Fig. 4. Structure of 2D optical fiber array.

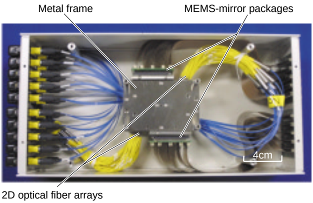


Fig. 5. Photograph of prototype optical switch module having 100 input and 100 output ports.

fabricated switch module having 100 input and 100 output ports. The optical components in the module were mounted on metal frames without any positioning mechanism and firmly fixed to each other using conventional dowel pins, instead of epoxy resin. The switch module has an overall hardware volume of approximately 170 cc (80 × 60 × 35 mm).

2.4 Mirror-motion control

MEMS mirrors generally work as high-Q resonators with relatively ineffective damping mechanisms. This severely limits the settling time of the MEMS-mirror tilt motion, which is mainly determined by the resonant frequencies and the damping factors of the mirrors. Therefore, another damping scheme is needed for high-speed switching operation. To solve this problem, a high-speed mirror motion controller with an open-loop control was developed [11].

Figure 6 shows a block diagram of the mirror-motion controller. The controller uses open-loop control and has three functional blocks: a waveform-shaping block, a digital-to-analog (D/A) converter block, and a high-voltage amplifier (Amp) block. The waveform-shaping block consists of a calculation unit for polynomial expressions to process the driving-signal stream applied to the MEMS mirror. Each coefficient in the expressions is obtained by an inverse-function calculation using mirror dynamics. This waveform-shaping operation eliminates vibration around the resonant frequency in mirror motion, thereby reducing the settling time. Figures 7(a) and (b) show the step responses of the mirror motion without and with the mirror-motion control. They confirm that the settling time for mirror motion is effectively reduced from 20 to 3 ms by using this mirror-motion control. We also developed a real-time servo control system for the MEMS mirrors, which maintains the stability of internal connections in the switch.

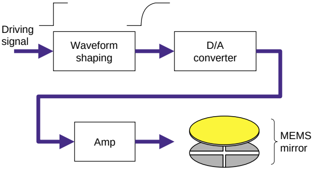


Fig. 6. Block diagram of mirror-motion controller.

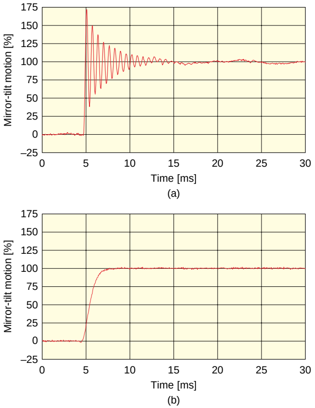


Fig. 7. Step response of MEMS-mirror motion (a) without and (b) with mirror-motion control.

3. Performance of a prototype switch module

First, we experimentally evaluated the optical characteristics of the switch module. The typical insertion loss of a port was 4.0 dB, the return losses were greater than 30 dB, the PDLs were less than 0.5 dB, and the crosstalk into adjacent ports was less than –60 dB, as shown in Table 1. These results experimentally confirm that our switch module has good optical characteristics for practical applications.

We also evaluated the switching operation of the module. Figure 8 shows an example of the 1 × 2 switching operation when driving voltages for the MEMS mirrors were under 50 V. The switching time was about 3 ms with the newly developed high-speed

Table 1. Summary of optical characteristics in the module.

Insertion loss	4.0 [dB]
Return loss	> 30 [dB]
PDL	< 0.5 [dB]
Crosstalk	< –60 [dB]

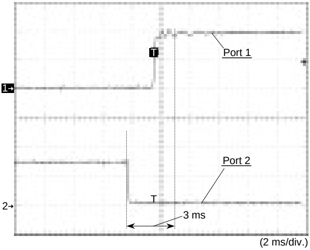


Fig. 8. Example of 1 × 2 switching operation.

mirror-motion controller, which demonstrates the feasibility of the compact low-cost 3D MEMS optical switch module.

4. Conclusion

We have developed a compact, low-cost switch module based on MEMS two-axis tilt mirror arrays and free-space optics using polymer components. The MEMS-mirror arrays consist of single-crystal silicon mirrors supported by high-aspect-ratio torsion springs that provide the highly durable mechanical structure needed for reliable connections in the switch module. The free-space optics, which comprise low-cost and highly accurate two-dimensional optical fiber and microlens arrays based on polymer components, are fabricated by passive assembly for low cost. Experimental results showed that a prototype switch module with 100-channel optical fiber input/output has a low coupling loss of 4.0 dB and switching time of 3 ms.

References

[1] K. Sato, N. Yamanaka, Y. Takigawa, M. Koga, S. Okamoto, K. Shiomoto, E. Oki, and W. Imajuku, "GMPLS-based photonic multilayer router (HIKARI router) architecture: An overview of traffic engineering and signaling technology," IEEE Comm. Mag., Vol. 40, No. 3, pp. 96-101, 2002.

[2] D. J. Bishop, C. R. Giles, and G. P. Austin, "The Lucent LambdaRouter," MEMS technology of the future here today, IEEE Comm. Mag., Vol. 40, No.3, pp. 75-89, 2002.

[3] V. Kaman, R. Anderson, R. Helkey, O. Jerphagnon, A. Keating, B. Liu, H. Poulsen, C. Pasarla, D. Xu, S. Yuan, and X. Zheng, "Optical performance of a 288 × 288 photonic cross-connect system," in Proc. of PS2002, paper-PS.TuA4, pp. 59-61, 2002.

[4] V. A. Aksyuk, F. Pardo, D. Carr, D. Greywall, H. B. Chan, M. E. Simon, A. Gasparyan, H. Shea, V. Lifton, C. Bolle, S. Arney, R. Frahm, M. Paczkowski, M. Haueis, R. Ryf, D. T. Neilson, J. Kim, C. Randy Giles, and D. Bishop, "Beam-steering micromirrors for large optical cross-connects," IEEE J. of L. T., Vol. 21, No. 3, pp. 634-642, 2003.

[5] R. Sawada, E. Higurashi, A. Shimizu, and T. Maruno, "Single crystalline mirror actuated electrostatically by terraced electrodes with high-aspect ratio torsion spring," in Proc. of Opt. MEMS 2001, Paper-C-1, pp. 23-24, 2001.

[6] J. A. Walker, "The future of MEMS in telecommunications networks," J. of Micro-mechanics and Microeng., Vol. 10, No. 3, R1-7, 2000.

[7] C. M. Schroeder, "Accurate silicon spacer chips for an optical-fiber cable connector," The Bell Sys. Tech. J., Vol. 57, No. 1, pp. 91-97, 1978.

[8] G. Proudley, C. Stace, and H. White, "Fabrication of two-dimensional fiber optic arrays for an optical crossbar switch," Opt. Eng., Vol. 33, No. 2, pp. 627-645, 1994.

[9] T. Yamamoto, J. Yamaguchi, and Y. Uenishi, "Low-cost and highly accurate two-dimensional optical fiber arrays for large-scale 3D MEMS optical switches," in Proc. of PS2002, paper-PS.WeC11, pp. 184-186, 2002.

[10] T. Satake, N. Kashima, and M. Oki, "Very small single-mode ten-fiber connector," IEEE J. of L. T., Vol. 6, No. 2, pp. 269-272, 1988.

[11] J. Yamaguchi, N. Takeuchi, A. Shimizu, T. Yamamoto, E. Higurashi, R. Sawada, and Y. Uenishi, "Characteristics and control of MEMS mirrors for optical cross-connect switch," in Proc. of MIPE03, Paper-OD-04, 2003.

Tsuyoshi Yamamoto
Research Engineer, Network Hardware Integration Laboratory, NTT Microsystem Integration Laboratories.

He received the B.E. degree in electrical engineering from Kansai University, Osaka in 1991. In 1991, he joined the NTT Communication Switching Laboratories, where he engaged in research and development on digital free-space optical switches and large-scale free-space optical interconnection systems. In 1998-99, he was a visiting research engineer at the Department of Electrical and Computer Engineering, McGill University, Quebec, Canada. Recently, he has been involved in research and development of 3-D MEMS optical switches for large-scale optical cross-connects. He is a member of IEEE.

Johji Yamaguchi
Senior Research Engineer, Network Hardware Integration Laboratory, NTT Microsystem Integration Laboratories.

He received the B.E., M.E., and Ph.D. degrees in mechanical engineering, all from Tokyo Institute of Technology, Tokyo in 1988, 1990, and 1993, respectively. He joined NTT Interdisciplinary Research Laboratories, where he is engaged in research on optical cross-connect systems. Recently, he has been involved in research on 3-D MEMS optical switches for large-scale optical cross-connects. He is a member of the Japan Society of Mechanical Engineers and the Japan Society for Precision Engineering (JSPE).

Renshi Sawada
Senior Research Engineer, Supervisor, Network Hardware Integration Laboratory, NTT Microsystem Integration Laboratories.

He received the B.E., M.E., and Ph.D. degrees in mechanical engineering from Kyushu University, Fukuoka, in 1976, 1978, and 1995, respectively. In 1978, he joined the Electrical Communication Laboratories of NTT in Tokyo. He has been engaged in research on the polishing of Si substrates, gettering of Si crystalline defects, fabrication of dielectrically isolated Si substrates, and optical MEMS such as a micromirror array, integrated optical displacement sensors, and an integrated optical blood flow sensor. He is a member of JSPE, the Institute of Electrical Engineers of Japan, and the Society of Instrument and Control Engineers. He received awards from JSPE in 1981 and 1991.

Yuji Uenishi
Senior Manager, Department V, NTT.

He received the B.E., M.S., and the Ph.D. degrees in applied physics from Osaka University, Osaka in 1982, 1984, and 1997, respectively. In 1984, he joined the NTT Electrical Communication Laboratories, where he had been engaged in research and development on micro-optical integrated devices. He studied MEMS technology as a visiting researcher at Case Western Reserve University, Ohio, U.S.A. from 1992 to 1993. Since returning to NTT Labs, he has been studying the technology for integrating MEMS and photonic devices, and has performed pioneering work on optical MEMS in Japan. He is a senior member of IEEE and a member of the Japan Society of Applied Physics. He received JSPE paper award in 1995 and the Micro Optics Conference paper award in 1997.