MEMS Technologies for Micro Optics
--- From Fiber Optic Communication to Display ---

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ABSTRACT

We report our recent research accomplishment in the field of optical MEMS (microelectromechanical systems) using the silicon micromachining technologies for both commercial-level product and laboratory-level research and development. Fiber optic VOA (variable optical attenuator) has been commercially released through close collaboration with industrial partner. Besides fiber optics, we also have target in the consumer electronics such as image projection displays using MEMS optical spatial light modulators. This paper also covers MEMS color pixels that could be potentially used to develop flexible electronic papers or posters.

INTRODUCTION

The history of Optical MEMS (Micro Electro Mechanical Systems) can be dated back to the early 1970's, when an array of micro mirrors made of silicon nitride and aluminum thin film was used to project bitmap images [1]. After almost a quarter century, micro optics has become large portion of the MEMS applications. As well as the projection-type display [2,3], a plenty of room has been discovered in the field of fiber-optic networks to demonstrate the potential of optical MEMS technology. In particular for the wavelength division multiplexing (WDM) systems, MEMS approaches have been already acknowledged to be an essential technology to develop wide range of active and passive optical components, namely, wavelength tunable laser diodes [4], optical alignment, variable optical attenuators [5, 6], optical crossconnect [7], and add/drop modules [8].

Advantages of using the MEMS approaches in micro optics are its excellent optical performance such as small insertion loss, small crosstalk, and large switching contrast. More importantly, optical MEMS devices enjoy full bandwidth of the optical fiber network thank to the "all-optical" capability that uses no opto-electro or electro-opto conversion. In the last few years, MEMS technology has become matured and has delivered drastic improvement of technical potential to micro optics. MEMS has also gained commercial strength to justify the cost-performance of their products, thanks to the improvement of production yield; device reliability in terms of external mechanical shock, temperature change, and moisture have been improved by the great efforts of engineers in this field, and now the reliability issues are systematically understood.

In this paper, we give a comprehensive overview of the up-to-date MEMS technologies that have been used in fiber-optic application devices and recent image display devices developed in our research group at the University of Tokyo in close collaboration with our industrial partners.

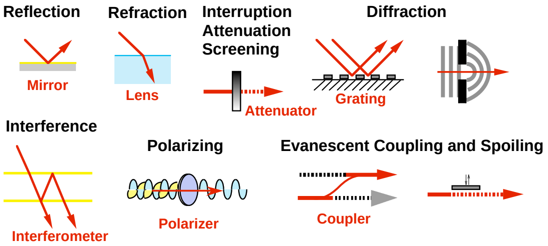


Figure 1 Principle of (spatial) light modulation by means of mechanical movement of optical components.

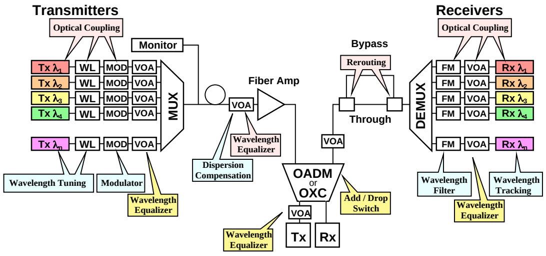


Figure 2 MEMS devices used in the optical fiber network.

MEMS FOR FIBER OPTIC APPLICATIONS
Mechanical solution for spatial light modulation

Figure 1 illustrates various types of spatial light modulation that could be implemented with mechanical motion of the optical components such as mirrors or prisms. Most optical MEMS devices today use reflection-type s modulators or scanning mirrors mainly because of the simplicity of MEMS fabrication processes as well as the negligible wavelength dependence of reflection. Nevertheless it should be addressed that the reflection is not the only mechanism of spatial light modulation but there are other possibilities such as refraction, diffraction, interference, polarization, and evanescent coupling; it implies that more chance in MEMS optical devices are left unexplored.

Fiber optic VOA

For the first example of industrial application, we directed our technology to develop fiber optic variable optical attenuators (VOA) in collaboration with Santec Corp., Japan [5]. Figure 2 schematically shows the fiber optic network connecting the transmitters (left) and receivers (right). The light signals of different wavelengths are generated by the laser diodes and modulated before combined into a single mode optical fiber; VOA is used each channel for intensity equalizer before the multiplexer. VOAs are also used on the receiver side to attenuate the intensity of the incoming light such that the receiver photodiode use the full dynamic range. Furthermore, VOA is used in the fiber amplifier to tune the incoming intensity to match with the dynamic range and linearity of the amplifier. In other words, VOA is the most attractive application target for the MEMS businesses.

Figure 3 schematically illustrates the MEMS structure of the VOA mirror scanner. We used the two optical fibers coupled with the mirror and the collimator lens, and control the coupling rate by the tilt angle of the electrostatic mirror. The circular mirror was made monolithically with the electrostatic actuator and the torsion hinges by using the active layer of silicon-on-insulator (SOI) wafer. On the other hand, the bottom part was made of the handle wafer of the SOI. The handle wafer was patterned into a shaped hole such that the actuator plate experienced unidirectional electrostatic torque under applied voltage. For high cost-performance fabrication and for the ease of technology-transferability to foundry services, we tried to make the MEMS fabrication process as simple as possible. Figure 4 shows the fabrication chart of the VOA (cross-section). In step-1, the SOI layer (30 microns) is patterned into the shape of the scanner by using the silicon high-aspect ratio etching technology as known as Deep RIE (reactive ion etching), and then protected with the passivation photoresist. In step-2, the backside of the wafer (500 microns) is etched in the same manner to the buried oxide (BOX, 2 microns thick). Finally in step-3, the movable structure is released by selectively removing the silicon oxide in the hydrofluoric acid. As a result, MEMS scanner was made in a 2 mm by 3 mm chip as shown in Figure 5. The mirror is 0.6 mm in diameter, and the actuator plate on the side is 80 microns by 400 microns each. The supporting hinges were designed to be short (100 microns long) and thin (1.7 microns wide) with the 30-micron-thick SOI layer to attain mechanical robustness against external vibration as well as low-voltage operation capability.

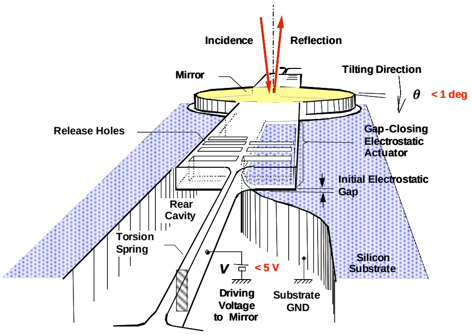


Figure 3 MEMS structure of electrostatic VOA mirror.

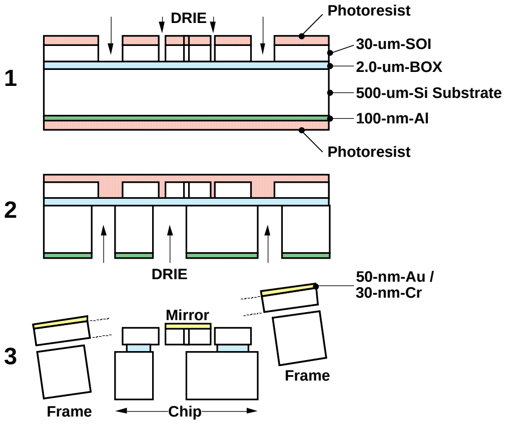


Figure 4 Fabrication process of electrostatic VOA with silicon-on-insulator wafer

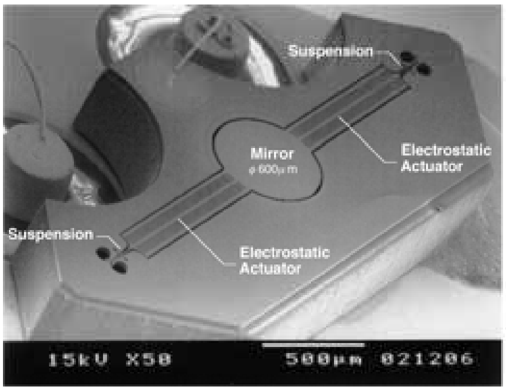
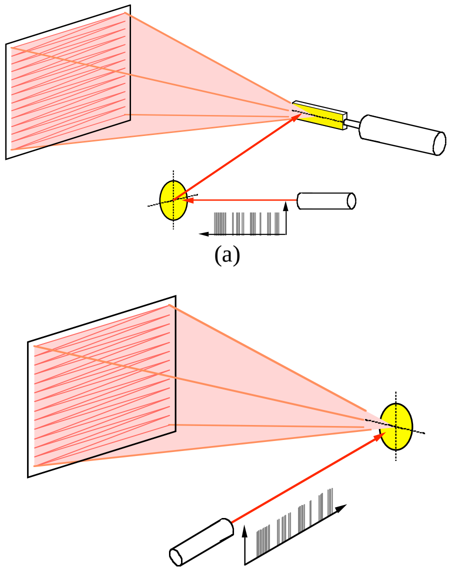


Figure 5 SEM image of developed MEMS VOA mirror.

MEMS PROJECTION DISPLAYS

MEMS Projection Display

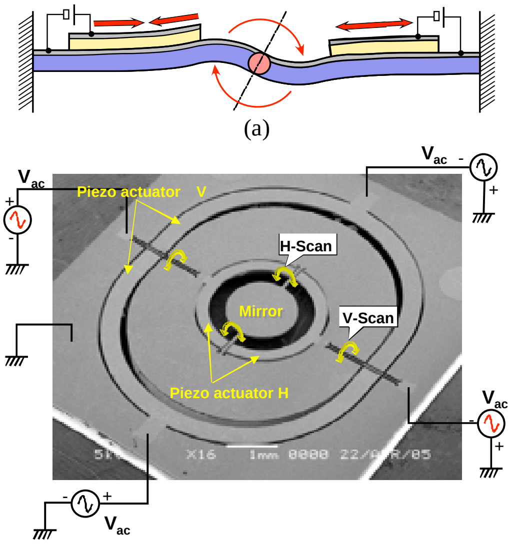
Similar fabrication technique of the silicon micromachining (DRIE) has been used to develop projection-type image displays. Figure 6 compares two different optical systems for creating images by mirror projection. The first scheme in Fig. 6 (a) uses one fast scanner for the horizontal axis with another slow scanner for the vertical axis [9]. The optical intensity from a laser is modulated synchronized with the scanner's mo-



(a)

(b)

Figure 6 Two different types of image projection system using MEMS scanners. (a) With a 2D scanner and (b) with a fast MEMS scanner and a slow galvano scanner.



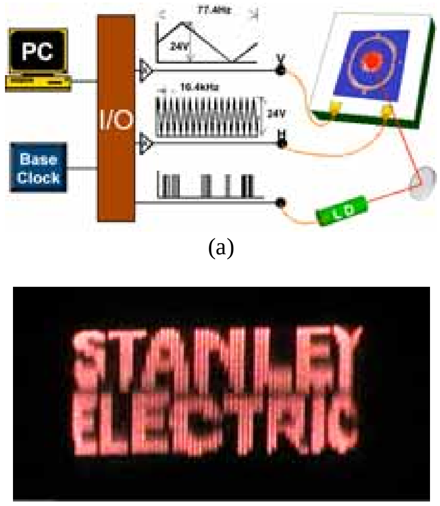
(a)

(b)

Figure 7 Optical 2D scanner with piezoelectric unimorph actuators formed into a double-gimal structure.

tion. Fast scanner is usually needed to create high-resolution images, and hence, MEMS scanner is expected to replace the conventional galvano scanners. On the other hand, the slow axis can be controlled by the conventional method such as a polygon mirror or a galvano scanner. The other scheme shown in Fig. 6 (b) is used to make a compact optical system of the equivalent capability by using only one scanner of two degrees of freedom as known as 2D scanner [10].

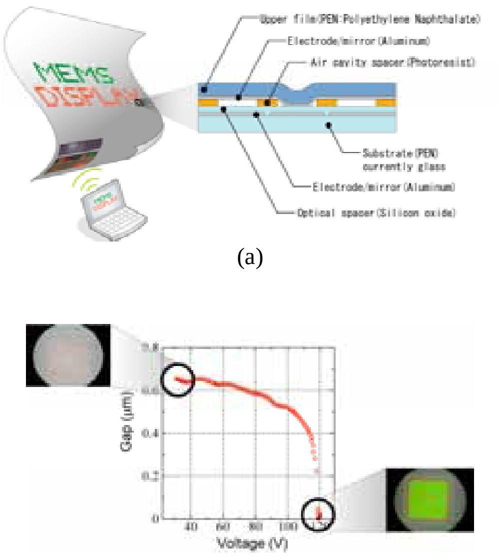
In collaboration with Stanley Electric Co., Japan, we have developed a 2D optical scanner using piezoelectric unimorph actuators. Piezoelectric PZT material was used to generate large torque as well as fast response.



(a)

(b)

Figure 8 Fabrication process of electrostatic VOA with silicon-on-insulator wafer



(a)

(b)

Figure 9 (a) MEMS structure of electronic color pixel based upon the Fabry-Perot interferomenter and (b) results of electrostatic operation.

Careful simulation has shown that the scanner's performance in general depends upon the areal force (torque) density of the actuator. Therefore, we used piezoelectric PZT film deposited on an SOI structure to for the actuator shown in Figure 7 (a). By applying differential bias voltages, one of the cantilever bends down while the other one bends up to rotate the bar connected in the middle. The rotation mechanism was used in the two axes for the horizontal- and the vertical-scan in the device shown in Figure 7 (b). The scanner structure was designed to have high contrast of resonant frequencies between the fast axis in the horizontal direction (optical 27 degrees at 16.4 kHz) and slow axis in the vertical direction (optical 32 degrees at

77 Hz) to have high resolution. The scanner was set under the test bench with a control PC and I/O board, as shown in Figure 8 (a), and was used to scan a laser beam of intensity modulation. Figure 8 (b) is the results of static bitmap display of 211 by 62. Currently the image resolution is limited by the computation speed of the I/O board, and it could be improved to maximum 1056 spots in the horizontal direction, calculated from the maximum scan angle and the mirror's number of resolvable spots.

MEMS Flexible Electronic Color Pixel

Different from the projection type display, we are also developing an e-Paper like displays by using a flexible plastic films formed into an interference color pixel [11]. Figure 9 (a) shows the idea of such color pixel that could be used like a sheet of paper. A pair of PEN (polyethylene naphthalate) films with a semi-transparent aluminum reflector (10 nm thick) is put together with a color-making layer of silicon dioxide (240 nm to 370 nm) and an air cavity. The air cavity is defined by the patterned photoresist, which also works as a glue layer. By applying dc voltage to the films, one of the PEN films is brought into contact with the counter film, where the air gap disappears and an interferometric color is shown. In case of a green pixel, we set the silicon oxide thickness to be 310 nm. For blue and red colors, the thickness is tuned to be 240 nm and 370 nm, respectively. Preliminary experimental results showed that the pixel of 600 um wide was operated to show the ON/OFF blinking at voltages of 120 V or higher as shown in Figure 9 (b). Details are reported by the co-author in this conference [12].

CONCLUSIONS

After almost thirty years of research and development, the optical MEMS has become an inspiring toolbox for creating advanced optical devices and systems. Micromechanically controlled optical elements can be used various kinds of fiber optic devices such as optical switches, gain equalizers, variable optical attenuators, and fiber dispersion compensators. Besides fiber optics, they have found new fields of applications such as image displays, free-space optical computing, pick-up head mechanism for optical data storages, and medical instruments. Micromechanically controlled optical elements in optical systems occupy the place equivalent to what transistors in VLSI (very large scale integration) system, which would be indispensable element in the future advanced electronics.

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