THE DEVELOPMENT OF AN 8 × 8 OPTICAL SWITCH

Yao-Joe Yang*, Bo-Ting Liao, Sun-Chih Shih, and Kuang-Chao Fan

ABSTRACT

In this paper, a novel 8 × 8 optical switch, which consists of a MEMS-based silicon micro-mirror array and a solenoid-based bi-stable mini-actuator array, is presented. The silicon micro-mirror array is realized by using a *single-step* anisotropic silicon etching process. The anisotropic silicon etching technique is capable of fabricating the self-aligned micro-mirror array with high accuracy and high fabrication yield. The mini-actuator array comprises 64 electromagnetic solenoid-based bistable actuators integrated with pushing arms. Each micro-mirror, which is connected to the substrate by a cantilever, can be individually actuated by a mini-actuator. Because of the bi-stability of the mini-actuators, the power consumption of the system can be significantly reduced. When the pushing arm does not contact the cantilever, the micro-mirror which is under zero external force can precisely reflect optical signals. When the pushing arm pushes up the micro-mirror, the optical signal passes through under the mirror. The main advantages of this proposed switch include high precision, high fabrication yield, low actuation voltage, low cost, low power consumption, and easy fiber alignment. The optical performance and the dynamic response of the switch are also investigated. The measured insertion loss is about -2.2 ~ -3.3 dB, cross-talk is less than -60 dB, and the measured switching time is less than 12 ms.

Key Words: optical microelectromechanical systems, optical switches, anisotropic silicon etching, bi-stable.

I. INTRODUCTION

The rapid growth of internet data traffic has been enabled by optical telecommunication networks (Yano *et al*., 2005). The building blocks of optical telecommunication system include optical fibers, optical sources, optical detectors, optical components, and so on (Dutton *et al*., 1998). Microelectromechanical systems (MEMS) technology has been widely employed to fabricate many optical components such as optical switches (Toshiyoshi *et al*., 1996; Marxer *et al*., 1997; Yamamoto *et al*., 2003; Ji *et al*., 2004; Bernstein *et al*., 2004; Horsley *et al*., 2005; Huang *et al*., 2006), variable optical attenuators (VOA) (Isamoto *et al*., 2004; Lee, 2007; Zhang *et al*., 2008) and optical add/drop multiplexers (OADM) (Pu *et al*., 2000; Li *et al*., 2004; Kwon *et al*., 2005). It is well-known that MEMS-based devices possess the advantages of high precision, compact size, enhanced performance, and low cost. Thus, MEMS technology has become a key technique for the optical telecommunication industry.

Optical switches play an important role in the optical telecommunication network for network provisioning and protection. Thus, it is essential to have optical switches with low insertion loss, fast switching time, and low cross-talk. Several types of MEMS optical switches have been extensively reported on previous works (Chen *et al*., 1999; Wang *et al*., 2004; Neilson *et al*., 2004; Su *et al*., 2005; Chu *et al*., 2005; Yang *et al*., 2007). MEMS optical switches with various actuation mechanisms, including electrostatic and electromagnetic actuation, have been demonstrated. In general, the required voltage for the electromagnetic actuation method is much less than that of the electrostatic method. Also, electromagnetic actuation is capable of generating a long stroke. In previously reported works (Houlet *et al*., 2002; Maekoba *et al*., 2001), MEMS-based optical switches that are based on the electromagnetic actuation have been fabricated by

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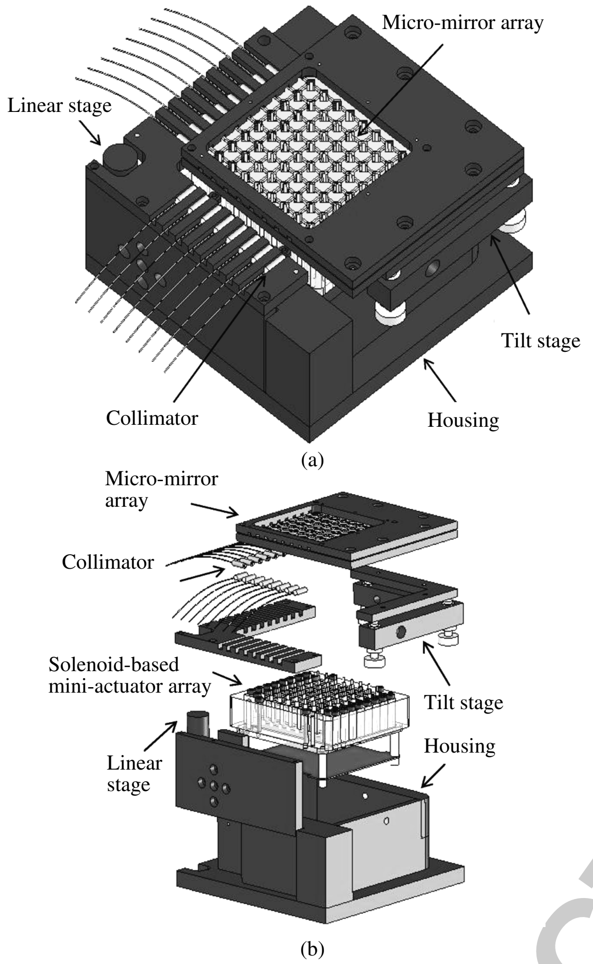


Fig. 1 (a) The schematic drawing of the proposed 8 ×8 optical switch. (b) The corresponding exploded view of the switch

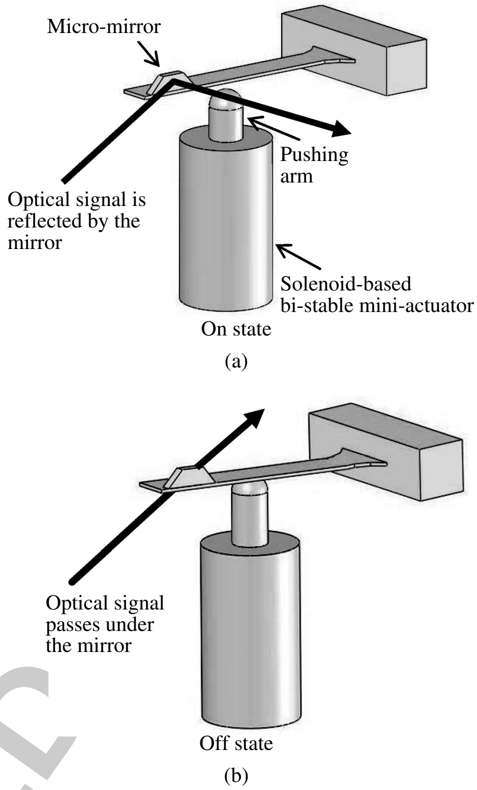


Fig. 2 The operational principle of the switch. (a) On state, the pushing arm does not contact the cantilever such that the micro-mirror can precisely reflect the optical signal. (b) Off state, the cantilever is pushed up by the pushing arm and the optical signal can pass through under the mirror

using the anisotropic silicon etching process (Helin *et al.*, 2000). However, in these optical switches, tiny blocks of permalloy must be glued on the micromachined structure, which increases the complexity of fabrication.

In this work, we propose a simple fabrication process and a reliable actuation method to realize an 8 ×8 optical switch. The proposed 8 × 8 optical switch includes a self-aligned silicon micro-mirror array and a solenoid-based bi-stable mini-actuator array. The silicon micro-mirror array, which comprises vertical mirrors, cantilevers, and light-path trenches, can be monolithically created by the proposed *single-step* anisotropic silicon etching process. Also, the proposed solenoid-based *bi-stable* actuators are used for the mini-actuator array. This bi-stable actuation approach not only reduces the complexity of the system driving circuit, but also eliminates the concern of device temperature elevation because of lower power consumption.

II. DESIGN

1. Design of Optical Switch

Figure 1(a) depicts the schematic drawing of the proposed 8 × 8 optical switch. The corresponding exploded view of the switch is illustrated in Fig. 1(b). As shown in the figure, the MEMS-based micro-mirror array is fixed on a tilt and linear stage which will be used to precisely adjust the system's optical alignment. The proposed solenoid-based mini-actuator array is mounted underneath the micro-mirror array for the actuation of the mirrors. The detailed design and fabrication of the solenoid-based mini-actuator can be found in a previous work (Shih, 2008). Each mini-actuator can retain the mirror at either one of the two stable positions without consuming any electrical power. The operational principle of the switch is shown in Fig. 2. The mini-actuator comprises a solenoid-based actuator integrated with a pushing arm. When the pushing arm does not contact the cantilever, the micro-mirror that is in the light path can precisely redirect optical signals to the desired output channels (ON state, as shown in Fig. 2(a)). When the cantilever is pushed up by the pushing arm, the optical signal can pass through under the mirror (OFF state, as shown in Fig. 2(b)). Note that the optical signal is reflected by the mirror only when the mirror and the cantilever are under zero external force. Therefore,

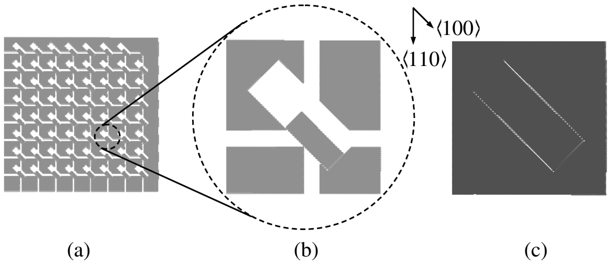


Fig. 3 (a) Mask layouts of the 8 ×8 micro-mirror array. (b) Enlarged view of the mask layout for one mirror and the light-path trenches. (c) Backside mask layout of one cantilever

the stress-free single-crystal silicon mirror can accurately reflect the optical signal and thus the optical loss of the switch can be greatly reduced.

2. Etching Masks of Mirror Array

The mask layouts for fabricating the 8 × 8 silicon micro-mirror array are shown in Fig. 3. In this work, a <100> silicon wafer is used for realizing the micro-mirror array which includes vertical mirrors, cantilevers, and light-path trenches. As shown in Fig. 3, the mask patterns of the mirrors are aligned with the <100> direction and the mask patterns for the light-path trenches are designed to be aligned with the <110> direction. Because the angle between <100> and <110> crystallographic directions is 45°, the surfaces of the etched mirrors that are formed on {100} planes can be self-aligned with the light-path trench along the <110> direction. In other words, the angle of 45° between the <100> and <110> directions is used for the self-alignment of the mirrors and the light-path trenches. Since the fabricated vertical mirrors can be self-aligned to the light-path trenches, the complexity of the fiber-alignment procedure can be possibly reduced.

III. FABRICATION

The proposed *single-step* anisotropic silicon etching process with KOH etchant is illustrated in Fig. 4. The process flow is viewed on the cross section of AA’. The starting material is a double-side polished (100) silicon wafer with thickness of 800 μm. First, the silicon wafer has silicon nitride layers deposited on both sides by using low pressure chemical vapor deposition (LPCVD). The silicon nitride layers will be used as the etching mask for the micro-mirror array. In order to obtain smooth etched sidewall surfaces (i.e., micro-mirrors), precise alignment of mask patterns to the <110> crystal orientation on a (100) silicon wafer is required. Several alignment methods have been reported to achieve precise mask alignment to the crystal orientation (Ensell *et al*., 1996; Lai *et al*., 1998).

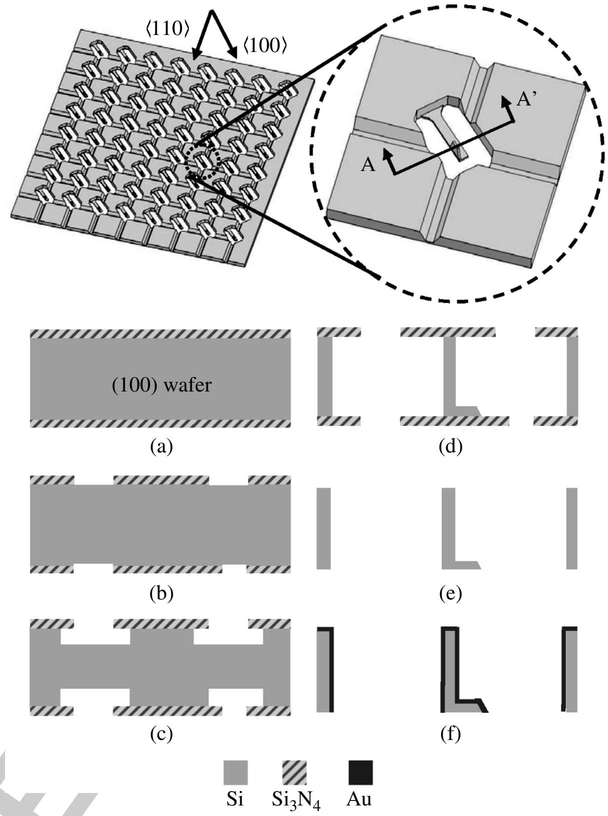
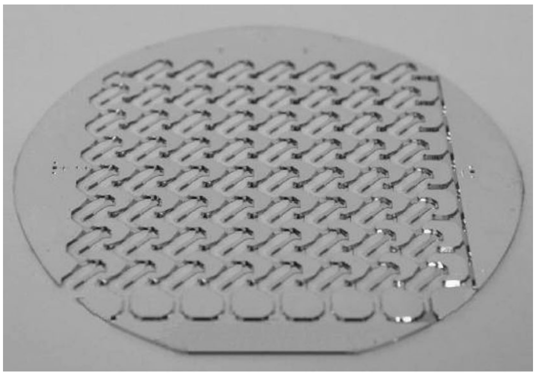


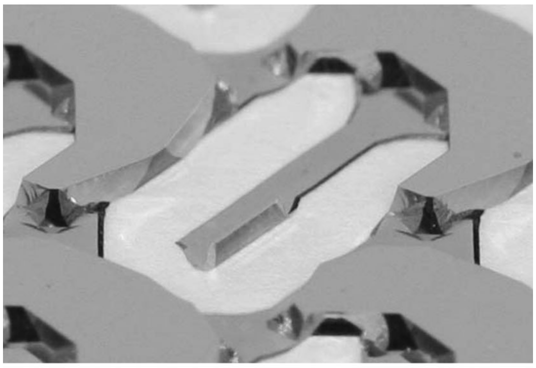
Fig. 4 The fabrication process of the silicon micro-mirror array. (a) The (100) silicon wafer is deposited with silicon nitride layers. (b) Patterns transferred. (c) The beginning of the KOH etching process. (d) The micro-mirror array is created after the KOH etching process. (e) The residual silicon nitride layers are removed. (f) The fabricated micro-mirror array is deposited with gold

After defining the mask openings of the cantilever array, the mask patterns of the mirrors and the light-path trenches are defined on the front-side of the wafer using a double-side mask aligner. The wafer that is patterned on both sides is then immersed in KOH etchant. Note that the patterns exposed to KOH etching are carefully designed by considering the lateral undercutting width during the etching process. The desired dimensions of the silicon micro-mirror array can be created after the etching process. It has to be emphasized that the micro-mirror array, including vertical mirrors, cantilevers, and light-path trenches, can be simultaneously created by using the proposed *single-step* anisotropic silicon etching process. As a result, the complexity of the fabrication process can be reduced and the process yield can be improved. Also, the etching temperature is 75°C.

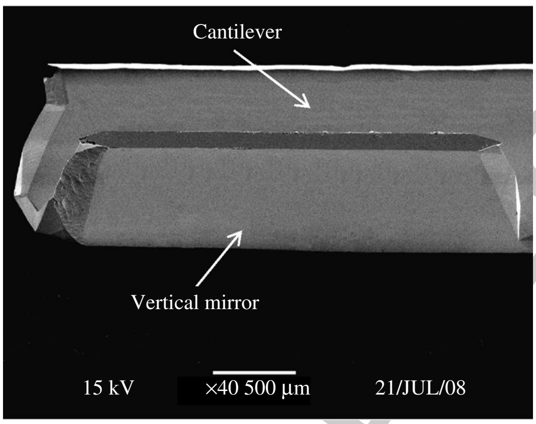
After the micro-mirror array is created, the residual nitride layers are removed by using phosphoric acid. Finally, a thin gold layer of about 2000Å is deposited on the device structures for improving the optical reflectivity of mirrors. Fig. 5(a) shows the



(a)



(b)



(c)

Fig. 5 (a) A picture of the fabricated 8 ×8 micro-mirror array. (b) An enlarged view of a cantilever with a movable mirror. (c) An SEM picture of the vertical mirror and the cantilever

fabricated 8×8 micro-mirror array. The enlarged view of a fabricated cantilever with a movable mirror is shown in Fig. 5(b) and the SEM picture is shown in Fig. 5(c). Note that the sidewalls of the cantilever are not vertical due to the fact that a higher etching rate occurs on convex corners. The typical dimensions of the fabricated mirrors and cantilevers are 2 mm × 0.72 mm × 0.08 mm and 8 mm × 1 mm × 0.08 mm, respectively.

IV. MEASUREMENTS

The prototype of the assembled 8×8 optical switch

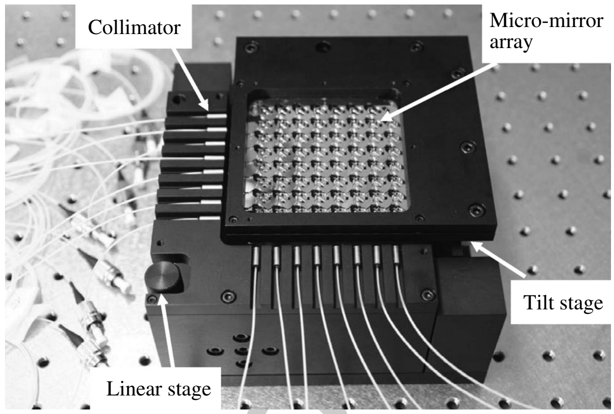
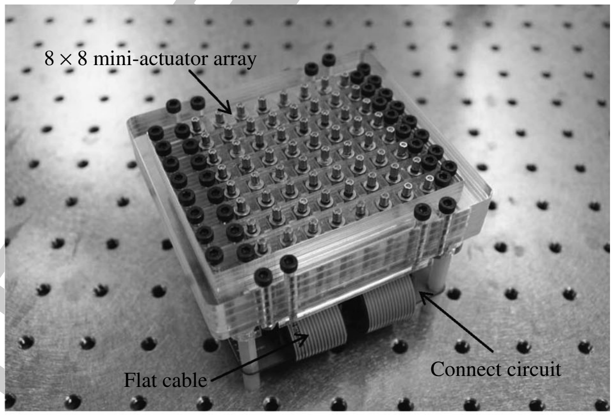
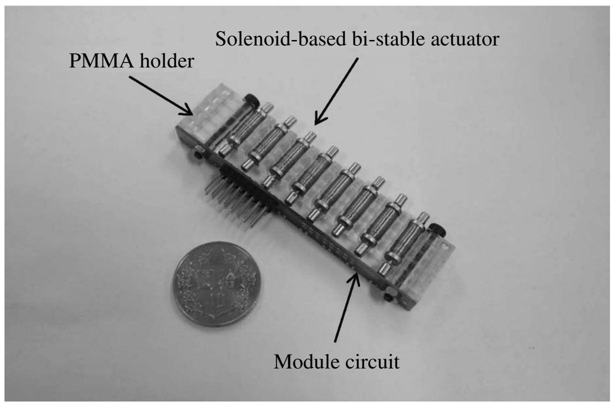


Fig. 6 The prototype of the assembled 8 ×8 optical switch



(a)



(b)

Fig. 7 (a) The 8 ×8 mini-actuator array assembled with eight solenoid-based bi-stable actuator modules. (b) The solenoid-based bi-stable actuator module

is shown in Fig. 6. As shown in this figure, the aluminum housing contains all of the switch components which include the MEMS-based micro-mirror array, a tilt stage, a linear stage, collimators, and a mini-actuator array. The mini-actuator array is composed of eight solenoid-based actuator modules, as shown in Fig. 7(a). Each actuator module, as shown in Fig.

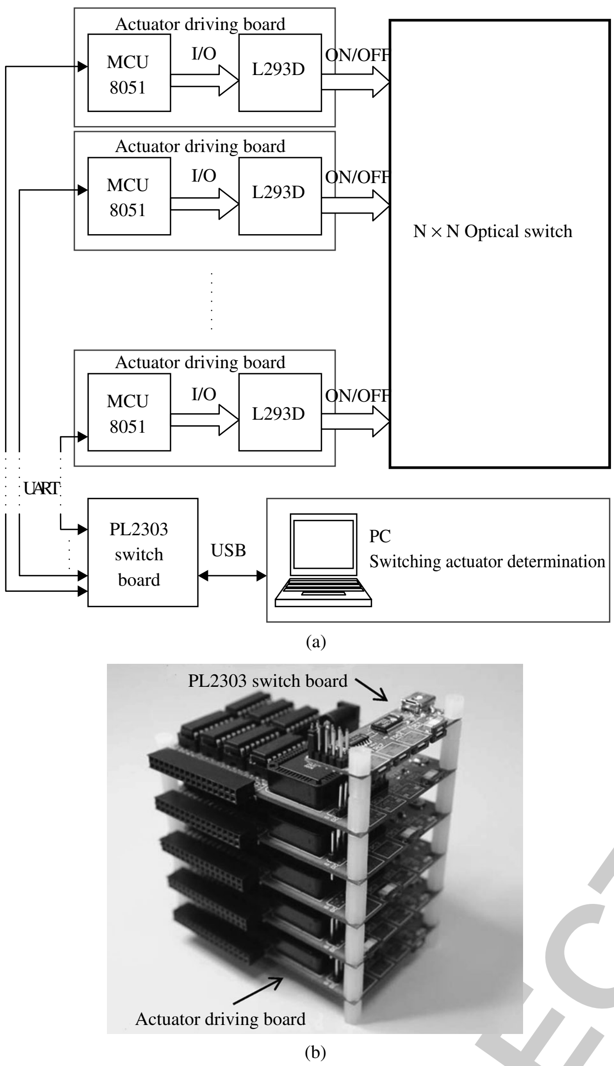


Fig. 8 (a) The schematic of the optical switch system. (b) The picture of the assembled circuit for driving the mini-actuator array

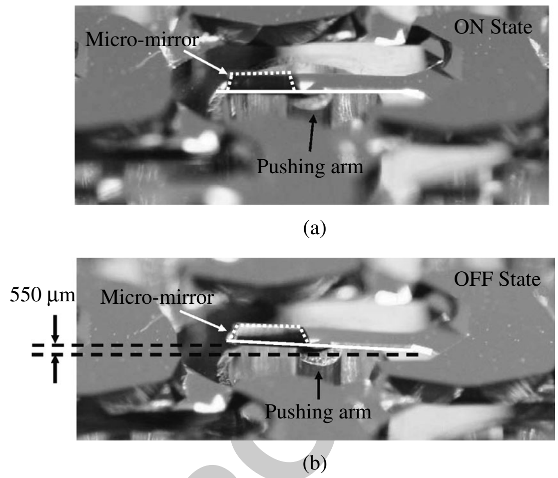


Fig. 9 (a) ON state, the cantilever is not contacted by the pushing arm and the mirror is at the first stable position. (b) OFF state, the cantilever is pushed up by the pushing arm and the mirror is at the second stable position

7(b), comprises eight solenoid-based bi-stable actuators. These eight solenoid-based bi-stable actuators are mounted in a PMMA (Polymethylmethacrylate) holder which is connected to a controller circuit.

Figure 8(a) depicts the schematic of the optical switch system. The optical switch is actuated by the driving circuits with 8051 microcontrollers. The actuator driving circuits can communicate with a computer via a USB interface. The assembled circuit, which includes five actuator driving boards and one switch board, is shown in Fig. 8(b). The optical switch is controlled by the computer.

The mini-actuator can switch the mirror between two stable positions with an input voltage of 6V. When the cantilever is not contacted by the pushing arm, the micro-mirror is at the first stable position (ON state, as shown in Fig. 9(a)). On the other hand, when the cantilever is pushed up by the pushing arm, the micro-mirror moves to the second stable position (OFF state, as shown in Fig. 9(b)). The minimum measured displacement of the mirror is about 550 μm which is large enough for a light beam to fully pass under the mirror. The typical dynamic response of the switch is shown in Fig. 10. The ON-OFF switching time, which is defined as the time when the mirror switches from the ON state to the OFF state, is about 6 ms, as shown in Fig. 10(a). Besides, the OFF-ON switching time, which is defined as the time when the mirror switches from the OFF state to the ON state, is about 12 ms, as shown in Fig. 10(b). Note that the small oscillation, as indicated in Fig. 10(b), arises from the vibration of the cantilever when it returns to the ON state, at which time the mirror reflects the light beam. Due to the phenomenon of small oscillation, the OFF-ON switching time is larger than the ON-OFF switching time. The optical performance of the switch is measured at the wavelength of 1550 nm. Fig. 11 shows the typical measured results of insertion losses for 100 switching cycles. The average measured insertion loss is between -2.2 dB and -3.3 dB. The deviation of the insertion losses is less than 0.07 dB. Another important optical performance of the switch is the cross-talk. The cross-talk is defined as the fraction of power transferred from an input port to an unintended output port. Therefore, when the optical power is launched into the input port and switched to a specific output port, the optical power which is measured at the other seven output channels is called the cross-talk. The cross-talk of the switch is measured by using a powermeter and the measured worst-case cross-talk is less than -60 dB, which matches Bellcore's requirement for optical switches.

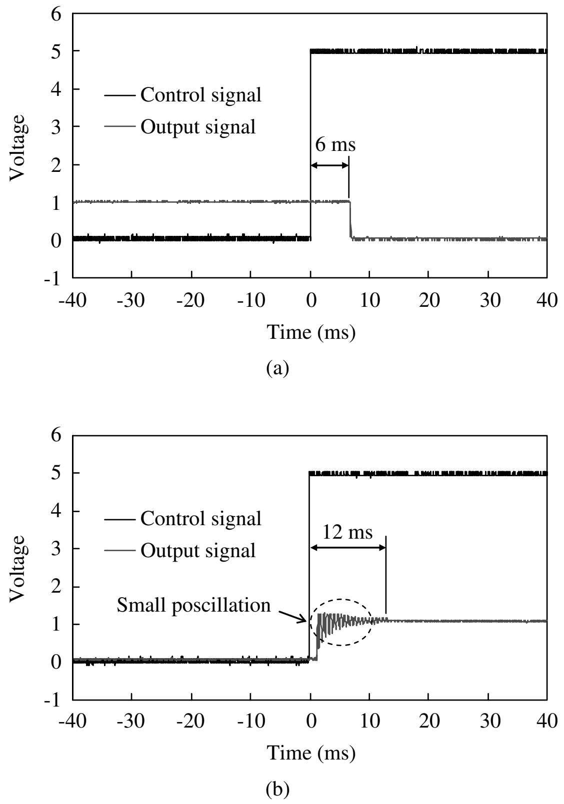


Fig. 10 The measured dynamic responses of the switch. (a) The mirror is switched from ON state to OFF state. (b) The mirror is switched from OFF state to ON state

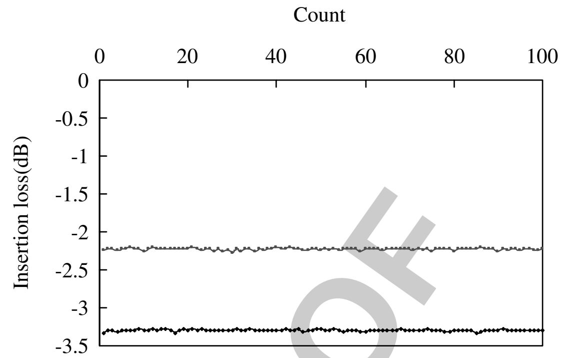


Fig. 11 The measured results of insertion losses for 100 switching cycles

V. CONCLUSION

The development of a novel 8 ×8 optical switch is demonstrated in this work. The proposed switch consists of a MEMS-based silicon micro-mirror array and a solenoid-based bi-stable mini-actuator array. The silicon micro-mirror array can be realized monolithically by using a proposed single-step anisotropic silicon etching process. The solenoid-based bi-stable actuators with actuation voltage of 6 V are utilized in the mini-actuator array. The measured ON-OFF and OFF-ON switching times are 6 ms and 12 ms, respectively. The average measured insertion loss is between -2.2 dB and -3.3 dB, and the deviation of the insertion losses is less than 0.07 dB. Also, the measured cross-talk is less than -60 dB. This novel switch possesses the advantages of high precision, high fabrication yield, low cost, low actuation voltage, easy fiber alignment and low power consumption.

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