A 2 × 2 Mechanical Optical Switch With a Thin MEMS Mirror

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***Abstract*—This paper presents the design, fabrication, alignment and experimental tests of a 2 × 2 mechanical optical switch. The key component of the mirror device is fabricated by the MEMS process that coats both sides with an ultrathin high reflection Au/Cr film (thickness less than 1.8 microns and roughness 5.7 nm) to allow double-sided reflection. The mirror is mounted on a thin metal arm, which is switched by a mechanical relay. Compared to the 4-mirror type of single-sided reflector which is used by other 2 × 2 optical switches, this configuration significantly reduces the size and number of the components. The optical alignment and the component assembly can rapidly be accomplished by two stages: visual coarse alignment and automatic fine alignment. Due to the feature of an adjustable mirror positioning and orientation, insertion losses can be reduced to a very low level. Experimental results show that the insertion losses, crosstalk, switching time and long-cycle test can all meet the Bellcore 1073 specification requirements.**

***Index Terms*—Light tracing alignment, mechanical relay, mirror reflection, optical switch.**

I. INTRODUCTION

OPTICAL communication networks are rapidly built around the world to provide high-speed and high-capacity transmission utilizing the technology of dense wave length division multiplexing (DWDM) [1]. Optical switches play an important role in fiber-optic communication for mapping wavelength from input ports to appropriate output ports based on their destination. Since an optical switch is an essential optical device for increasing the reliability of optical fiber communication systems, the realization of a practical optical switch is a must for the fiber-to-the-home (FTTH) development. The requirements for an optical switch include compactness, low power consumption, excellent optical performance, and low cost.

At present, most 2 × 2 optical switches in research and commercial domains belong to six different types: 1) using the pin-referenced indirect slide principle to fabricate a 2 × 2 mechanical optical switch [2]; 2) using a prism as reflective component moved by a relay or a motor to switch the optical beam [3], [4]; 3) using micromirrors fabricated by MEMS technologies and controlled by an electrostatically or thermally comb-driven actuator to switch the optical beam [5]–[17]; 4) using micromirrors fabricated by "Semi" MEMS technologies and controlled by an additional magnetic field from "an iron yoke and a self-wound coil" [18]; 5) using the micro hot embossing process to fabricate the vertical micromirror and polycarbonate as structure material of the optical switch platform [19]; and 6) piling up 1 × 2 or 1 × 4 switches with looped-back fibers configuration [20], [21]. From the reflective-mirror point of view, common design applies four micromirrors of single-sided reflection that would normally cause a large dimension and more components [22]–[24]. A number of researchers applied a MEMS process, such as DRIE, to fabricate a double-sided reflection mirror that could reduce the number of mirrors to one [6]–[12], [16]–[18], [25]–[32]. The thickness of the thin mirror and the difficulty to adjust the mirror due to the all-MEMS processes will affect the insertion loss. In addition, using an electrostatic actuator will cause a high driving voltage.

The authors' group has devoted to the design of 1 × 2 and 1 × 4 optical switches with a mechanical relay as actuator [33]–[35]. Small relays with low cost, low voltage drive, fast switching time, and latch function can easily be purchased from the market. Sophisticated tasks for the fabrication of actuators by the MEMS processes can be omitted. In this paper, a similar relay technology in conjunction with a new ultrathin and double-sided reflective metal film fabrication technology is proposed for a new 2 × 2 switch design. The mirror is mounted on a thin metal arm, which is switched by a mechanical relay. Due to the feature of an adjustable mirror position and orientation using a fine motion multistage, insertion losses can be reduced to a very low level by employing the developed light tracing algorithm for the automatic fine alignment. The total assembly and packaging time can thus significantly be reduced. Experimental results show, that the insertion losses, crosstalk, switching time, and long-cycle test can all meet the Bellcore 1073 [36] specification requirements.

II. THE DESIGN OF THE 2 × 2 OPTICAL SWITCH

This switch utilizes four collimators, which are arranged at an angle of 90° to each other on a common base plate, in order to emit and receive the light in parallel beams at a certain distance. The switching principle of the 2 × 2 optical switch is shown in Fig. 1(a) and (b), respectively. When the mirror is moved away from the reflection position, the input light will directly enter into the respective output channels (namely, ch1 → ch3; ch2 →

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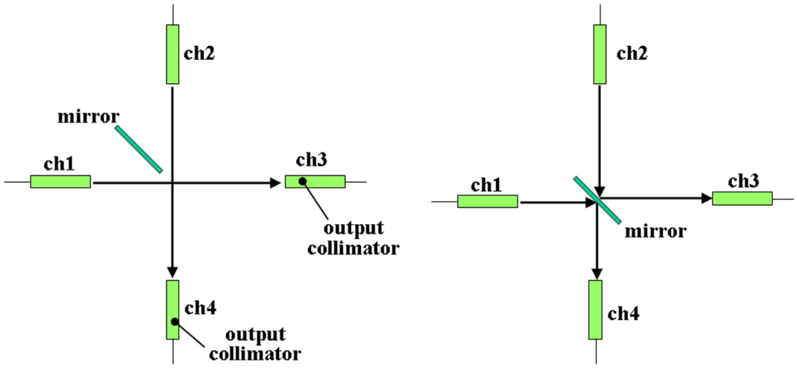


(a) (b)

Fig. 1. The principle of the optical path. (a) Transmission state. (b) Reflection state.

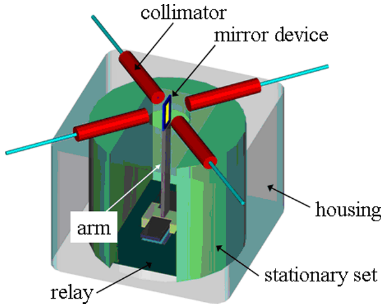


Fig. 2. Schematic diagram of the 2 × 2 mechanical optical switch.

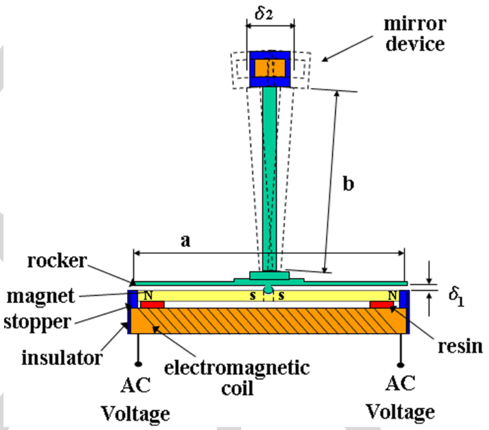


Fig. 3. The relay switching mechanism.

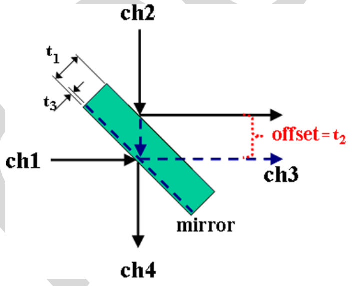


Fig. 4. The optical path offset due to the thickness of the mirror.

ch4). When the mirror is moved to the reflection position, the optical beams will be bent to the alternate output channels (namely, ch1 → ch4; ch2 → ch3) simultaneously from both sides of the thin metal film. The structure is composed of two modules: the mirror module and the collimator module. The mirror module consists of a base plate, a relay, an arm, and a mirror device; the collimator module consists of four collimators and the housing. The base plate is fixed at the housing; both are made of low thermal expansion Invar steel. The relay is based on the principle of electromagnetic forces to switch the rocker and latch to the stopper. After the light alignment process, the final package is accomplished by applying the UV epoxy glue and UV curing to the collimators and the base. The schematic diagram of the developed 2 × 2 optical switch is shown in Fig. 2. The mechanism of the mirror device and the relay components are shown in Fig. 3. When applying a driving voltage of 5 V with a current of 40 mA to the relay, the rocker will switch from its rest position to the other stopper position by a 0.2-W power consumption so that the mirror device will change its states accordingly, namely to the transmission-state and the reflection-state. Compared to normal 2 × 2 switches that employ four thick mirrors of only one-sided reflection, this design is much more compact. The special feature of a thin-film mirror and its fabrication process will be addressed in the following.

A. *Optical Path Design and Loss Analysis*

The reflective type of the 2 × 2 optical switch is often influenced by the thickness of the mirror (t_1), which causes an inevitable offset and misalignment (t_2), where $t_2 = \sqrt{2}t_1$, as is shown in Fig. 4. This increases the insertion losses of the output channels during the reflection state [37]. In order to minimize the loss, the thickness (t_1) of the mirror must be made as thin as possible, as depicted by t_3 in Fig. 4.

Most of the existing all-MEMS-based 2 × 2 switches have the thickness limitation in the mirror fabrication process, which employs a vertical etching from the top to the bottom of the substrate, producing poor perpendicularity and surface roughness of the sidewalls. These defects directly influence the insertion loss at the reflection state. Taking into account the physical strength of the thin film and the restriction in the process parameters, it is not easy to produce a thin reflective film using the traditional MEMS process by vertical etching. A new method will be described in Section III.

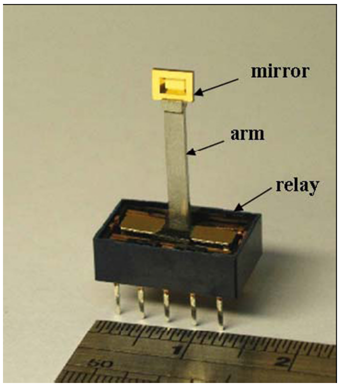


Fig. 5. The photograph of the switching mechanism.

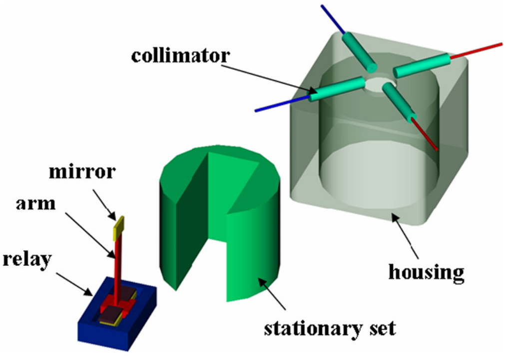


Fig. 6. The schematic and exploded view of the 2 × 2 optical switch.

In addition to the thickness effect, the coupling loss due to the lateral offset is related to the selected coupler. It is found that the adoption of a collimator leads to less coupling losses compared to the cleaved fiber and the lens-fiber [38], [39].

B. Design of the Switching Mechanism

A mechanical relay, commercially available from Panasonic Co. (Model TQ2-L2–5V), with the size of only $5 \times 9 \times 14\ \mathrm{mm}^3$, is adopted as actuator to drive the mirror device and its connected arm (made of a thin metal plate). When a voltage of 5 V is applied to the relay the generated magnetic force will switch the rocker as well as the mirror device to another position so that the input beam will change between the reflection state and the transmission state. In Fig. 3, the length of the arm (b), the rocker (a) and δ_1 are 15, 9, and 0.45 mm, respectively. The switching displacement of the mirror is about 1.5 mm. The relay has a latching function in order to maintain the state. A photograph of the switching mechanism and the CAD exploded view of the designed 2 × 2 optical switch are shown in Figs. 5 and 6, respectively.

III. FABRICATION AND MEASUREMENT OF THE MIRROR DEVICE

A. Fabrication of the Mirror Device

The silicon substrate was placed horizontally. The final structure shown in Fig. 7 was sequentially fabricated by the following eight processes.

Step 1) Thermal oxidation
A silicon dioxide film was thermally grown to a thickness of 350 A.

Step 2) Nitride and polysilicon deposition.
Silicon nitride and polysilicon films were deposited by LPCVD, yielding a thickness of 1000 A and 1 $\mu\mathrm{m}$, respectively.

Step 3) Cr/Au sputtering.
The metal films of Cr and Au were sputtered onto the front-side of the wafer substrate, yielding a thickness of 500 and 3000 A, respectively.

Step 4) Front side PR coating and backside polysilicon removing.
In this step, the wafer was etched by TMAH and the backside of the polysilicon was etched without protection.

Step 5) Backside pattern definition.
The photoresist was spun onto the backside of the wafer for patterning.

Step 6) Oxide/Nitride removing.
The backsides of the oxide/nitride were removed by RIE.

Step 7) TMAH etching.
The wafer was etched by TMAH and the backside of the silicon was etched until the oxide layer was exposed.

Step 8) Backside Cr/Au sputtering.
The metal films of Cr and Au were sputtered on the backside of the wafer, yielding a thickness of 500 and 3000 A, respectively.

B. Measurement of Mirror Thickness and Roughness

Fig. 8 shows the composition of the layers of the thin mirror micrograph taken by SEM. The total thickness is less than 1.8 $\mu\mathrm{m}$. It is the thinnest mirror compared to existing MEMS-based 2 × 2 optical switches this paper has referenced. Furthermore, since the surface roughness plays a very important role for the reflection of the optical beam, it is also desirable to ensure an acceptable smoothness of the mirror surface [19]. In order to measure the roughness of the mirror surface, an AFM (Park Scientific Instruments /AUTOPROBE M5) was used. The calculated RMS roughness in the area of 256 × 256 data points is 5.7 nm.

IV. ALIGNMENT AND INSERTION LOSS DETECTION SYSTEM

The optical system of the 2 × 2 switch consists of four single-mode optical fibers with each of its ends inserted into a collimator, a 1550 nm light source (Lightwave Co. model LWL-ASE-C-20) and a power meter (Anritsu-Mu931421A). The collimator emits a parallel beam with a spot size of 500 $\mu\mathrm{m}$ to an effective distance of 50 mm. Because of the symmetrical structure, the head to head distance of each paired collimators is about 50 mm. The alignment system aims to adjust the positions of the input collimators, output collimators and the mirror device by a light tracing task. This is implemented by two procedures, the coarse alignment and the fine alignment processes. We use an IR-Card and image process system for the coarse alignment, and then a power meter and alignment algorithm for the fine alignment. The IR card can show the spot light of the laser and the

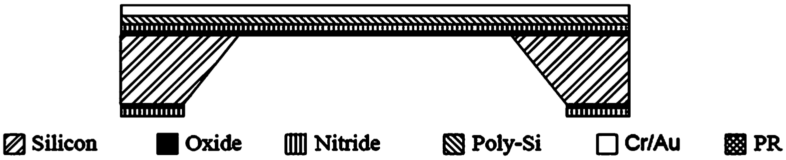


Fig. 7. The structure of the thin mirror.

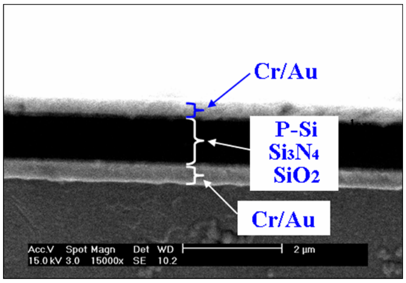


Fig. 8. SEM thickness image of the mirror.

image process system can capture the spot light image to calculate the misalignment of collimator. During the coarse alignment, both the paired input and output collimators emit light, as shown in Fig. 9(a). An IR card is placed in the middle of the light path so that both sides of the beams are visible, as shown in Fig. 9(b). Fixing one collimator, the positions and orientations of the other collimators are adjusted in sequence by the assistance of a 6-axis micro stages and a gripper, to allow both sides of the beams to be visually coincident when the IR card is moved back and forth between the two aligned collimators, as shown in Fig. 10.

It is subsequently followed by the fine alignment procedure with the assistance of a dual channel power meter and the developed light tracing optimization program. The procedures are:

1) Connect O_1 to the power meter. Feedback the power readings to the light tracing program which outputs a command to move the 6-axis micro stage in order to fine adjust O_1.
2) Repeat this process until the power reading converges to minimum. Thus, the fine alignment of O_1 to I_1 is completed. O_1 can subsequently be fixed by UV epoxy and UV curing.

A similar procedure can be applied to align O_2 to I_1 and finally I_2 to O_1 in sequence. Fig. 11(a) shows the developed 6-axis micro motion stage with the gripper. Fig. 11(b) shows the recorded insertion losses during the alignment steps of O_1 to I_1. The coarse alignment can help to obtain an insertion loss of less than 5 dB, while the fine alignment improves it further to less than 1 dB.

Generally speaking, the alignment process of a 2 × 2 switch is carried out manually in the optical switch company that takes several hours to complete one set. With the proposed vision-assisted automatic method, the coarse alignment can be done within about 15 min and the fine alignment can be completed within 5 min. A substantial time saving is obvious. The photograph of a completed 2 × 2 switch with connectors is shown in Fig. 12. The interior parts dimension is 24.5 mm × 24.5 mm × 22 mm and the packaged overall size is 34.5 mm × 34.5 mm × 32 mm.

V. EXPERIMENTAL RESULTS

A. *Insertion Loss Tests*

The used optical collimators have an outer diameter of 3.2 mm and a working distance of 20 mm. According to the Bellcore 1073 specifications, the insertion losses of two output channels of a 2 × 2 optical switch have to be simultaneously smaller than 1 dB [39]. The switch is under a test run of 100 cycles after it is aligned and packaged. The results of the mean insertion losses of the two output channels at the transmission state are in the range of: ch3: −0.28 dB to −0.29 dB, ch4: −0.55 dB to −0.562 dB and at the reflection state: ch3: −0.543 dB to −0.562 dB, ch4: −0.57 dB to −0.581 dB, respectively, as shown in Fig. 13. All are smaller than 1 dB. It is understood that due to the mirror effect the losses of reflection state are higher than the transmission state.

B. *Switching Time Test*

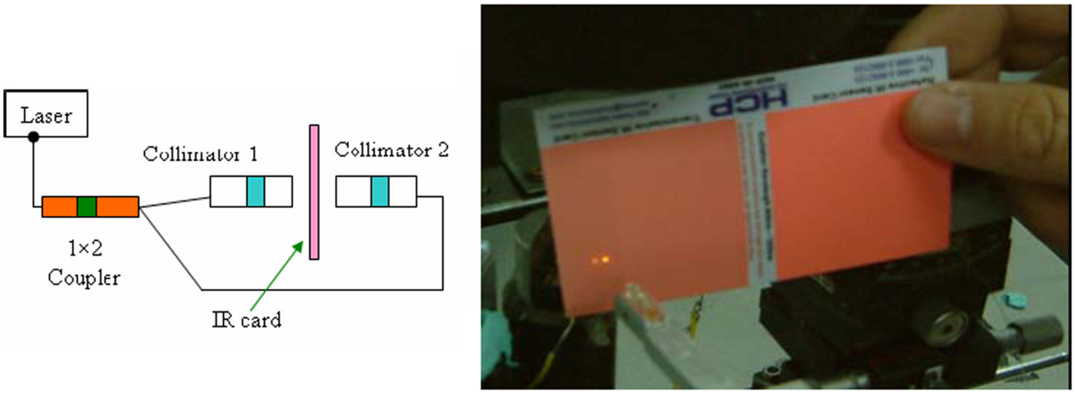
A step voltage is applied to the electromechanical relay and the optical signal from the output fiber channel is received by a photo diode. Both the input and output voltages are recorded by an oscilloscope. The switching time is recorded from the start of the input electric signal until the steady-state condition of the optical output signal has been reached. Fig. 14 shows that both the on-state and off-state switches can be completed within 4 ms.

C. *Crosstalk Tests*

This experiment is to switch the mirror back and forth, and uses a power meter to record the values of ch3 and ch4 simultaneously. When the optical path goes from ch1 to ch3, the signal which ch4 receives from ch1 is regarded as the crosstalk. Likewise, when the optical path goes from ch1 to ch4, the signal which ch3 receives from ch1 is regarded as the crosstalk. In our test, the signal is extremely low, which indicates almost no crosstalk.

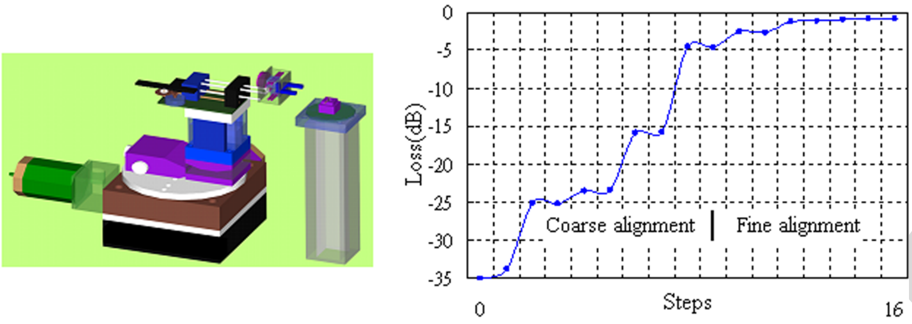
D. *Long-Term Reliability Tests*

In order to demonstrate the long-term reliability, the switch has passed a further test run of 10 000 cycles. As shown in Fig. 15, at the transmission state the variation of light intensity in ch3 is between 0.53 and 0.57 dB, and between 0.62 and 0.7 dB in ch4; while at the reflection state the variation in ch3 is between 0.74 and 0.78 dB, and between 0.79 and 0.84 dB in ch4.



(a) (b)

Fig. 9. Coarse alignment method: (a) Setup. (b) Both sides of the beams are visible.



(a) (b)

Fig. 11. Automatic alignment (a) 6-axis stage with gripper. (b) Insertion loss response.

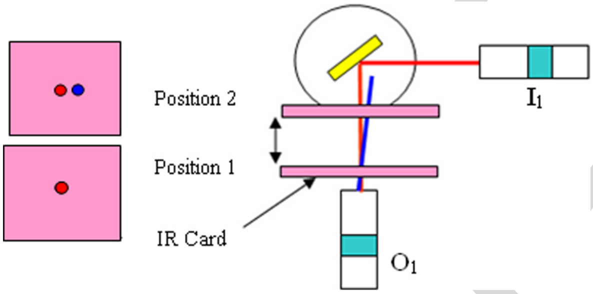


Fig. 10. Coarse alignment process.

The maximum variation of the insertion loss is < 0.08 dB. The performance meets the BELLCORE 1073 specifications.

VI. CONCLUSION

As reported in this paper, a simple, miniature and low cost 2 × 2 mechanical optical switch has successfully been developed. Its packaged size is 34.5 mm × 34.5 mm × 32 mm. It uses the advantages of MEMS fabricated thin films to enable double-sided reflection and an electromechanical relay which can easily be obtained from the market. Experimental results show that the mean insertion losses of the two output channels are less than 0.6 dB. The achievement of such small insertion losses is mainly due to the adjustable mirror and a fine alignment procedure. The quick switching time is about 4 ms and the crosstalk is very small. In order to test the long-term reliability a continuous switching of 10 000 cycles was applied. The

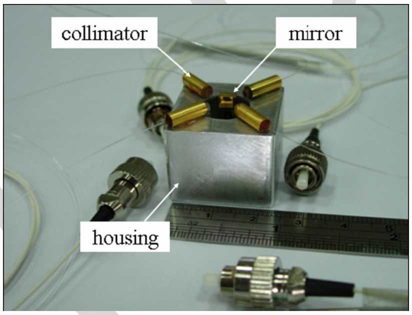


Fig. 12. Photograph of a 2 × 2 mechanical optical switch.

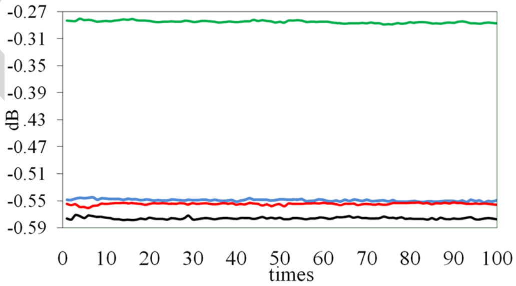
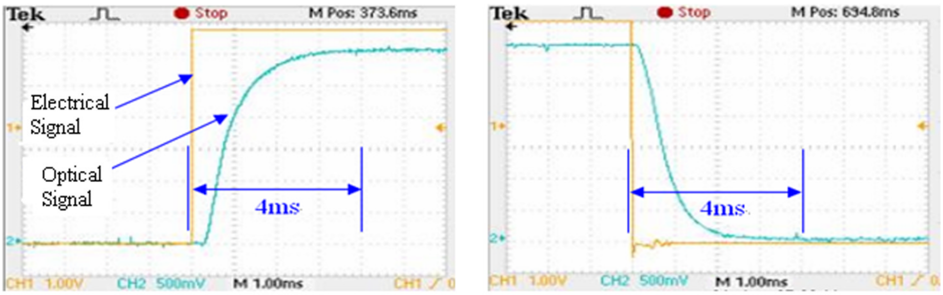


Fig. 13. The insertion losses of outputs during 100 cycles: The top line is the transmission state of ch3, the second line is the reflection state of ch3, the third line is the transmission state of ch4, the bottom line is the reflection state of ch4.

maximum variation of the insertion loss is < 0.08 dB. The per-



(a) (b)

Fig. 14. Switching time tests: (a) ON-state. (b) OFF-state.

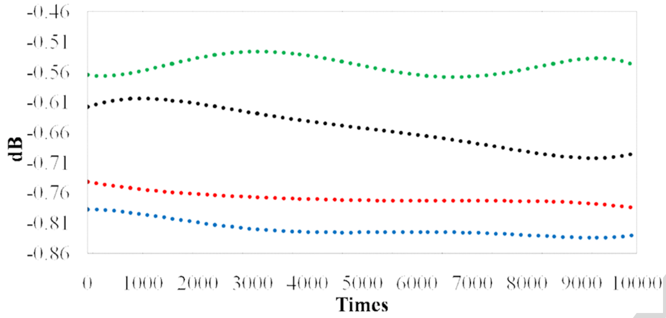


Fig. 15. The insertion losses of ch3 and ch4 during 10 000 cycles: The top dotted line is the transmission state of ch3, the second dotted line is the transmission state of ch4, the third dotted line is the reflection state of ch3, the bottom dotted line is the reflection state of ch4.

formance meets the Bellcore 1073 specifications. In addition, using the proposed automatic coarse and fine alignment procedures, we provide a simple light trace method with an IR-Card to assist the fabrication process of the 2 × 2 mechanical optical switch.

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