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A novel micro/nano 1 × 4 mechanical optical switch

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Abstract
This paper presents the design, fabrication and testing of a novel 1 × 4 mechanical optical switch, whose components are fabricated by precision machining and MEMS technologies. The switch uses two relays as the two actuators whose switching direction is perpendicular to each other by an orthogonal arrangement. We adopt a direct fiber-to-fiber principle that aligns the input fiber directly to four output fibers. This configuration eliminates the use of traditional parts such as collimators, turning mirrors or prisms. In addition, due to the use of a fiber holder, the fiber position errors could be reduced to less than 0.27 μm using the two-stage geometry error reduction principle. We have successfully developed a simple and low-cost switch, which performs like most of the 1 × 4 mechanical optical switches that dominate the optics communications market. The advantages of our switch are a small size ($20 \times 20 \times 25$ mm^3), low cost, high reliability, and the latching function does not need external force for maintaining the state. The experimental results showed that the insertion losses of the four channels are ch1: 0.68 dB, ch2: 1.49 dB, ch3: 0.71 dB and ch4: 0.97 dB. The switching time is 5 ms, the crosstalk $\leqslant$80 dB. The reliability tests of the insertion loss after 10 000 cycles in four channels yield ch1: 1.67 dB, ch2: 1.63 dB, ch3: 0.75 dB and ch4: 0.98 dB. The size and the cost of our 1 × 4 mechanical optical switch are only about 1/5–1/10 and 1/10 of the series-connect-type and prism-type switches, respectively.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Popularization of the internet network causes growth at a speed that doubles every 9 months on average. The technology of dense wavelength division multiplexing (DWDM) enables coupling and transmitting signals of different light wavelengths in one single fiber. Therefore optical switches are needed to make the best use of DWDM for the moderate distribution of the data flow [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. Hence, the popularization of optical switches is one of the keys for future DWDM network development.

The mechanical-type optical switch will play an important role for the business market of the DWDM network. It does not require the transformation of the optical signal between O/E/O as with the conventional method. Thus, it has the advantages of a low insertion loss and a low crosstalk, but its disadvantages are large size and high costs [2]. Fan *et al* [3] had successfully produced a novel 1 × 2 mechanical optical switch that is small in size ($20 \times 16 \times 7.5$ mm^3), of low cost (US$10) and highly reliable compared with other mechanical types of optical switches. Our switch is the smallest and cheapest among all existing 1 × 2 mechanical optical switches today.

At present, most of the 1 × 4 mechanical optical switches in the research and development field are constructed as follows: (1) it uses three 1 × 2 optical switches to make up a

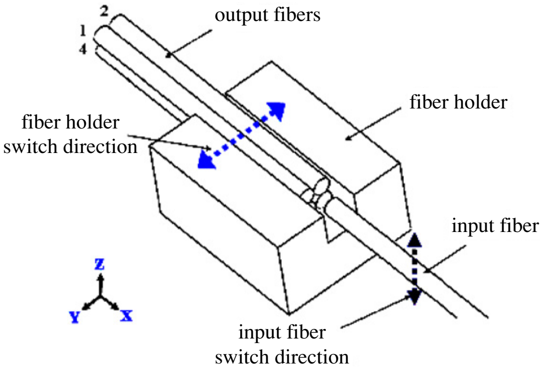


Figure 1. The fiber-to-fiber configuration.

1 × 4 optical switch by series-connect configuration [4, 5]; (2) it uses micro-lenses to reflect the input signal to four output signals [6, 7]; (3) it uses micro components fabricated by MEMS technology as the actuator [8, 9], the micro-mirror [10–13] or the fiber-driver [14] in order to reflect or switch the input signal. However, all these switches have some disadvantages as large size, high cost and manual alignment.

To overcome these disadvantages we have adopted the fiber-to-fiber configuration as an optical transfer mode, which vastly reduces the size and the cost by a simpler structure with increased yield. So far, we have developed the simplest and low-cost switch in comparison with all existing 1 × 4 mechanical switches that prevail in the market. Details of this system are described below.

2. Design of a 1 × 4 mechanical optical switch

2.1. 1 × 4 switch mechanism design

We use the direct fiber-to-fiber configuration as the 1 × 4 optical transfer mode. Four output fibers are precisely installed inside a fiber holder produced by MEMS technologies, and the input fiber, which is held with a ferrule, precisely aligns to four output fibers by the stopper effect of a fiber holder. The fiber-to-fiber configuration is shown in figure 1. The 1 × 4 switching mechanism can achieve the fours channels switching function by the relay's control circuit which is commanded by a LABVIEW program installed in a computer. The relay photograph and the actuation method are shown in figures 2(*a*) and (*b*), respectively. Applying a 5 V voltage and a 40 mA-driven current to the relay the rocker will switch to the other stopper positions with 0.2 W power consumption. The switching mechanism of this 1 × 4 mechanical optical switch is shown in figure 2(*c*). The first switching mechanism is composed of a relay-1 and a ferrule. The ferrule is mounted on the rocker of relay-1 with UV glue and the input fiber is inserted as an input channel. The first mechanism function is to drive the input fiber upward or downward by a 125 μm displacement as shown in figure 3. This mechanism is responsible for switching to the ch1–ch4 and ch2–ch3 directions as shown by the vertical arrow. The second switching mechanism consists of a guide on a central axis and two stoppers controlled to move into two distinct positions, named right stopper and left stopper positions, providing a switching of the input fiber to the right or the left position. The guide in turn is connected and switched by a soft rubber, which is mounted on a rocker of relay-2 to switch the ch1–ch2 and the ch3–ch4 directions, indicated by a horizontal arrow as shown in figure 3.

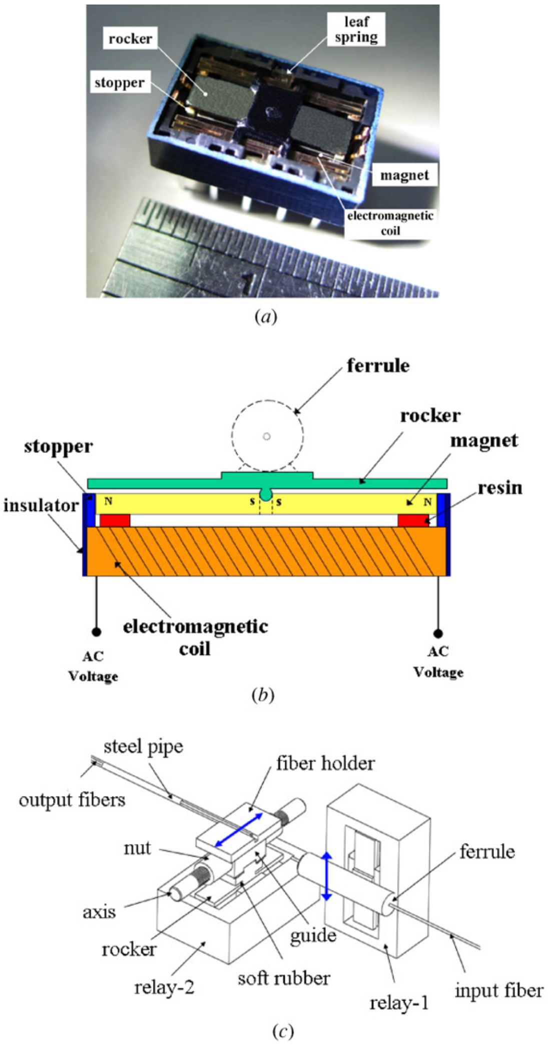


Figure 2. (*a*) Relay photograph, (*b*) actuation method and (*c*) the switching mechanism of the 1 × 4 optical switch.

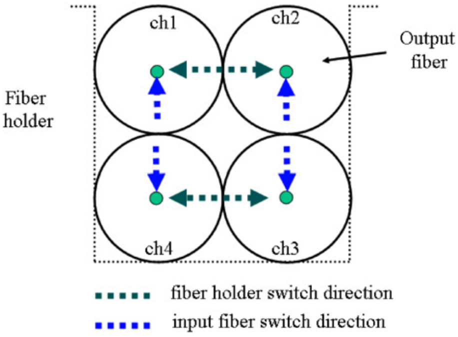


Figure 3. The switching direction of the 1 × 4 optical switch.

2.2. Drive circuit of the two relays

For the logical control of the relay's switching directions in order to achieve the 1 × 4 switch function, we designed a

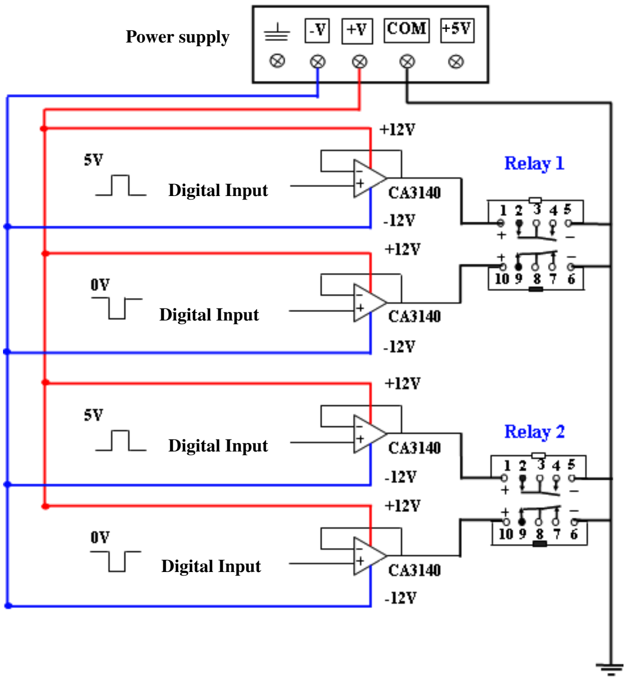


Figure 4. The control circuit of the two relays.

relay drive circuit, which is controlled by a LABVIEW program installed in a computer, controlling the switching direction of the input fiber and the output fibers upward, downward, right or left. We use a DAQ card (digital-to-analog converter) of PCI-6713, National Instruments Co., to send the control signal and amplify the drive current through an operational amplifier (OP) to command the relay switching. When the LABVIEW program commands an input 5 V voltage at pin no. 1 and a 0 V voltage at pin no. 10 of relay-1 the input fiber is switched upward. When the voltages of pin no. 1 and pin no. 10 of relay-1 are reversed, the input fiber is switched downward. Similar to the connection mode of relay-1, the fiber holder is switched rightward or leftward by reversing the voltage at relay-2. If the switching direction is diagonal as for the ch1–ch3 or ch2–ch4 direction the program applies simultaneously the voltages for relay-1 and relay-2 at pin no. 1 and pin no. 10. The drive circuit layout of the two relays is shown in figure 4. The actuator of the switch has a latching function which needs no external force for maintaining the state.

2.3. Holding the output fibers

In order to assure a precise holding and installation of the four output fibers inside the U-groove of the fiber holder a ‘steel pipe’ with an inner diameter of 0.305 mm and an outer diameter of 0.508 mm is used to preliminarily cluster the four output fibers together. The minimum circumferential diameter (MCD) of four output fibers in a 2 × 2 array is 0.3018 mm, so that the four output fibers could be inserted into the steel pipe by manual operation. The assembly of the pipe and the four fibers is shown in figure 5(*a*). The tolerance between the steel pipe and the MCD will not affect the proper alignment of module-1 and module-2. The function of the steel pipe is to hold the relative position between the four fibers. The steel pipe is glued in the U-groove of the housing unit. In our system, the front ends of four output fibers are fixed and UV glued in the U-groove of the fiber holder unit. The fiber holder is fabricated by the MEMS process which has a precise U-groove dimension of nearly 250 × 250 μm that is equivalent to the required square form dimension of four fibers (each fiber has the diameter of 125 μm). Four fibers are thus precisely placed and fitted in the U-groove of the fiber holder, as shown in figure 5(*b*). The fabrication process of the fiber holder is described in section 3.

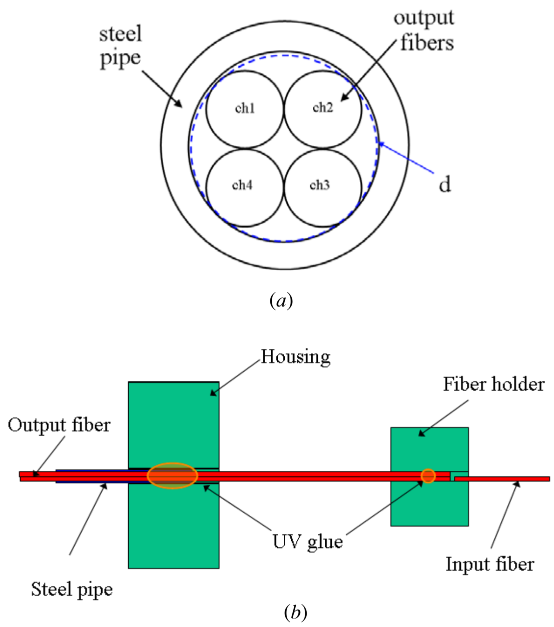
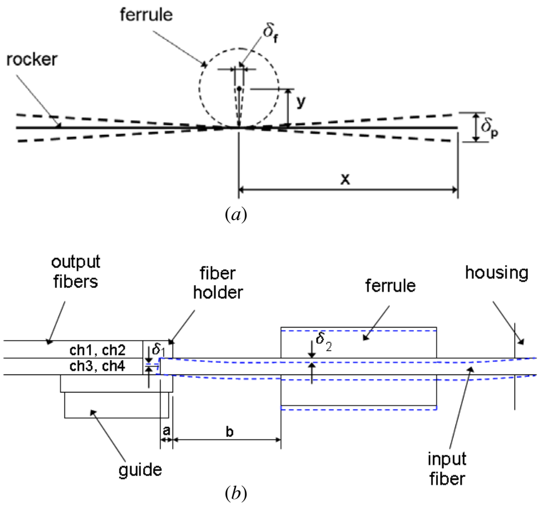


Figure 5. The assembly of the pipe and the four output fibers.

2.4. Error reduction of the switch mechanism

Mechanical relays, made by OMRON Co., have an inherent switch-positioning error of 10 μm at the end position (δp), as shown in figure 6(*a*). The length of ‘x’ and ‘y’ is 5.5 mm and 1.48 mm, respectively. On the basis of the lever principle, this amount can be reduced down to 2.7 μm at the end position of the y-arm (δ_f), which is the location of the ferrule. Moreover, as shown in figure 6(*b*), the ferrule positioning error can be reduced further to below 0.27 μm according to the second trigonometric relation of the fiber stopper pivot mechanism. The length of ‘b’ and ‘a’ is 5 mm and 0.5 mm, respectively. If there is no stopper in the fiber holder, the lateral misalignment δ_2 ($=\delta_f$) of the input fiber causes the same amount of misalignment of the output fibers because they are straight and parallel. The effectiveness of the stopper acts like a second lever mechanism and, due to the ratio of the arm lengths (a/b about 1:10), the lateral misalignment (δ_1) could significantly be reduced in proportion. For our 1 × 4 optical switch, the smallest switch-position error could be as small as 0.27 μm at ch3 and ch4.



(*a*)

(*b*)

Figure 6. Principle of the geometrical error reduction.

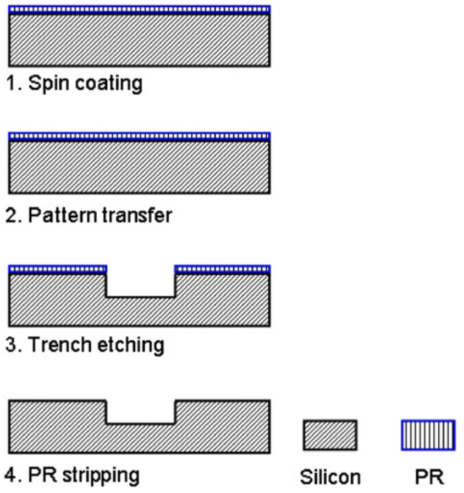
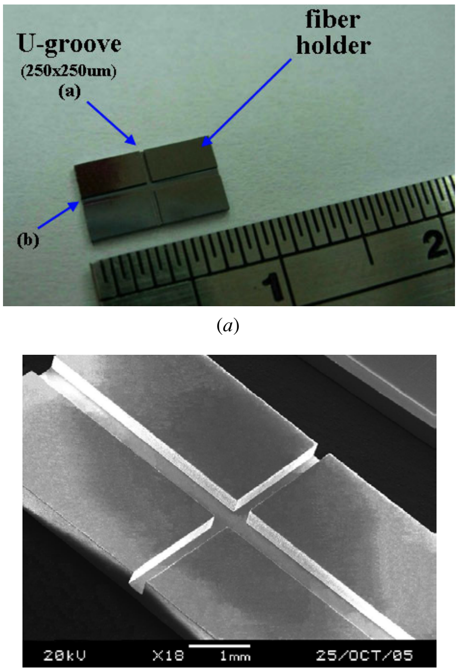


Figure 7. The fabrication process of the fiber holder.

3. Fabrication of the fiber holder

The size of the fiber holder is designed to be 8 × 4.5 × 0.5 mm^3 and the dimensions of the U-groove are 250 μm in width and 250 μm in depth, respectively. The U-groove can hold the output fibers very precisely. On the basis of these requirements, we use the (1 0 0) silicon wafer as the substrate. The substrate has a thickness of 500 μm, and the deep silicon etching technology of bulk micromachining is applied to groove etching. During the deep silicon etching, a high etch rate, a high selectivity to the mask and the anisotropic sidewall profile are necessary. In order to maintain these requirements during etching, the technique of sidewall passivation is proposed [15]. The process uses inductively coupled plasma (ICP) sources by a procedure proposed by BOSCH GmbH (the BOSCH process), [16] which effectively balances the steps between etching and passivation, thereby satisfying the concurrent etching requirements. The fabrication process for the fiber holder is shown in figure 7 and a detailed description is given as follows.



(*a*)

(*b*)

Figure 8. Photo and SEM picture of the fiber holder device.

Step 1: spin coating. To increase the adhesion between the photoresist and the wafer surface, a layer of hexamethyldisilazane (HDMS) is applied to the substrate surface prior to the coating of photoresist (PR) AZ4620 by spin coating.

Step 2: pattern transfer. The pattern of mask is transferred to the photoresist by a lithography process.

Step 3: trench etching. The BOSCH process with an ICP-RIE etcher is used and then a trench is etched down to a depth of 250 μm.

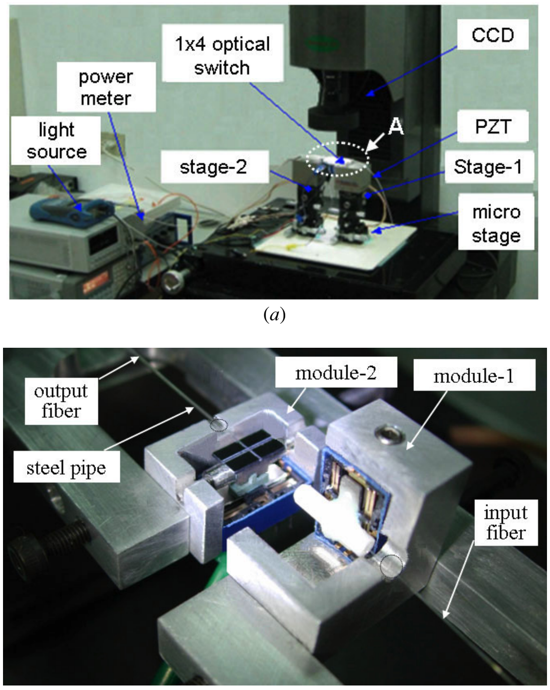
Step 4: PR stripping. In this step, the PR is removed by acetone.

The fiber holder device in our design has two U-grooves. The size of the first U-groove is 250 μm in width and 250 μm in depth as shown in part (a) of figure 8(*a*). Its function is to precisely hold the four output fibers. The size of the second U-groove is 500 μm in width and 250 μm in depth as shown in part (b). Its function is to bond easily the four output fibers and the fiber holder with UV glue. Figure 8(*b*) shows the SEM (scanning electron microscope) picture of the fiber holder device.

4. The alignment and loss detection systems

4.1. The alignment system

The alignment system is an integration of a CCD module, a micro stage module and an optical detector module. The alignment process is achieved by an image capture from the CCD module followed by an initial movement of the micro stage. Misalignment information is obtained and analyzed by the optical detection module; the processed data are then



(*a*)

(*b*)

Figure 9. (*a*) The experimental setup of the packaging and alignment system and (*b*) a close view of area ‘A’.

fed back and used to compensate for the fiber misalignment by a second stage movement. The experimental setup of the alignment system is shown in figure 9. The apparatus for an alignment system comprises the CCD module including a CCD capture set and an image processing system, two micro stages, an optical detection module including a 1310 nm light source, a power meter and a 1 × 4 coupler.

4.2. The loss detector system

The optical detector system consists of a LABVIEW program, a 1310 nm light source (EXFO-FLS-300), a power meter (Anritsu-Mu931421A) and a 1 × 4 multi-mode coupler (FOCI-Multimode). The 1 × 4 optical switch is put between the light source and the 1 × 4 coupler. When the input fiber aligns to the output fibers the power meter begins to show the insertion loss value and records it by the LABVIEW program over the GPIB cable connection. The screen shows the insertion loss values of the four channels simultaneously in real time. The optical detector system is shown in figure 10.

5. The switch package

5.1. The module package of the switch

The switch is packaged with module-1 and module-2 mounted on stage-1 and stage-2, respectively. A set of stages includes a micro stage and a PZT stage. Module-1 consists of a relay (relay-1), a ferrule, an input fiber and housing-1. Module-2 consists of a second relay (relay-2), a guide, an axis, two stoppers, four output fibers and housing-2. First we mount a ferrule on the rocker of relay-1 with UV glue and measure the input fiber switch displacement in order to confirm that it is 125 μm when relay-1 is switched. The package of module-1 of the 1 × 4 mechanical optical switch is completed after relay-1 is installed inside housing-1. At the next step, packaging module-2, we insert four fibers into the ‘steel pipe’ in order to hold the four fibers initially before they are installed inside the fiber holder. To fine adjust the nut positions between the two stoppers, we can control a very precise switch displacement of 125 μm by the measurement system. The guide is driven by a soft rubber which connects the guide and the rocker of relay-2 for transfer motion. Then, module-2 has been completely packaged after settling or bonding those components by UV glue. An illustration of module-1 and module-2 together with a thin upper housing case is shown in figure 11.

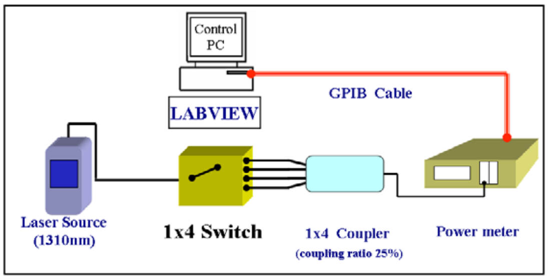


Figure 10. The layout of the optical detector system.

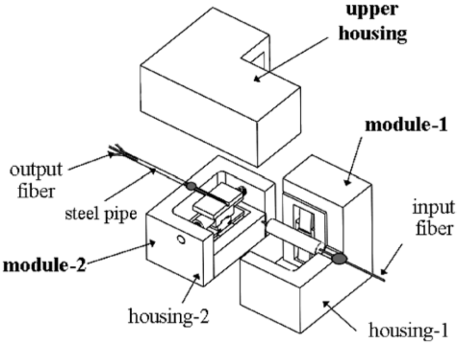


Figure 11. Module-1 and module-2 of the 1 × 4 optical switch.

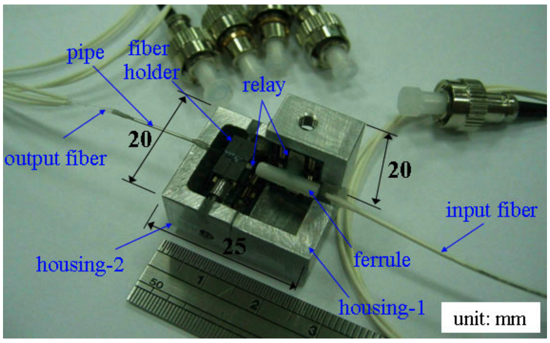
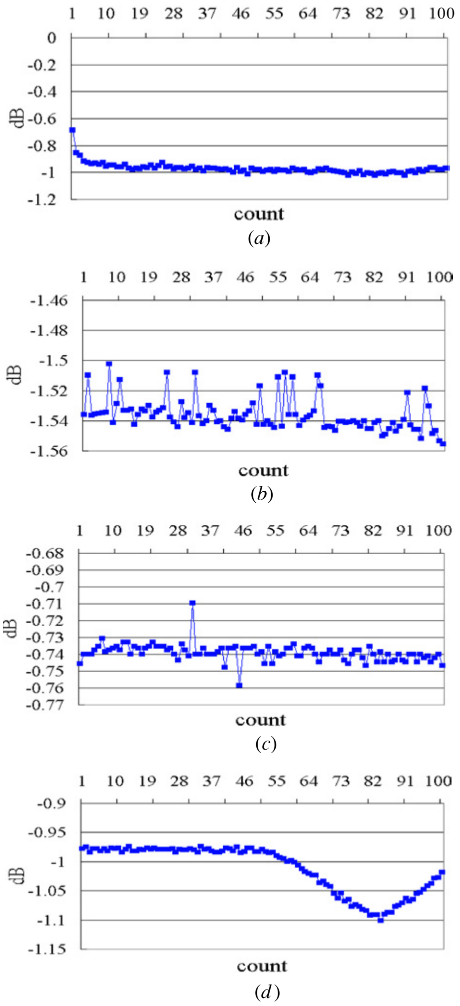


Figure 12. A photo of the developed 1 × 4 mechanical optical switch.



(*a*)

(*b*)

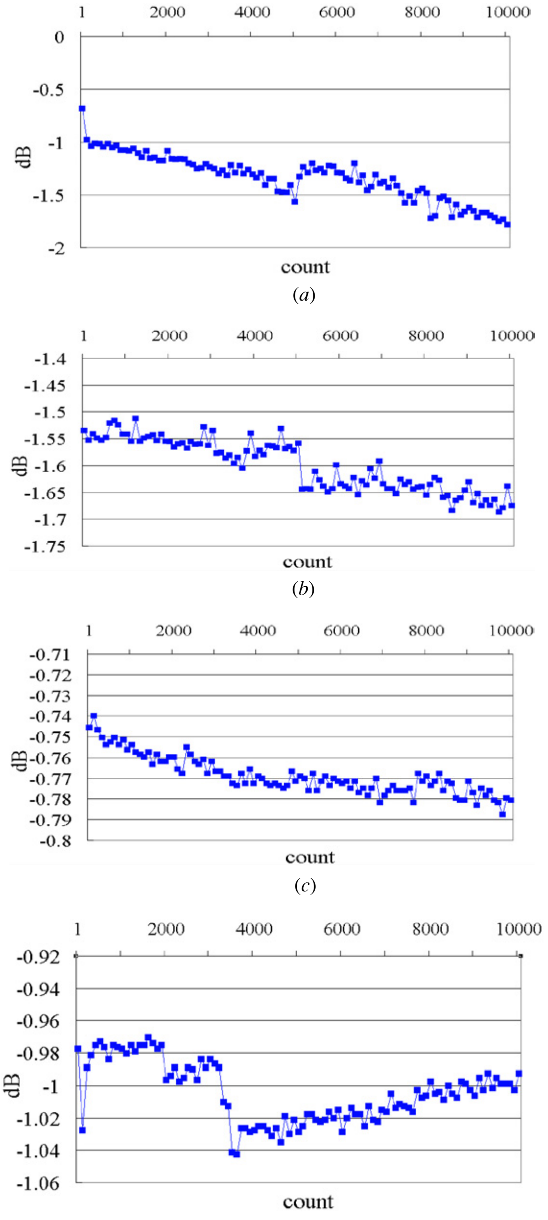
(*c*)

(*d*)

Figure 13. The insertion losses of the initial 100 times cycle test: (*a*) the insertion loss of ch1, (*b*) the insertion loss of ch2, (*c*) the insertion loss of ch3 and (*d*) the insertion loss of ch4.

5.2. The alignment method of the 1 × 4 switch

The alignment system has been set up completely after the input fiber of module-1 is connected to the 1310 nm light source, and the output fibers of module-2 are connected to the 1 × 4 coupler and the power meter. According to the original parameter design of our 1 × 4 optical switch for the alignment and packaging task, first, by adjusting the micro stage, the input fiber becomes close to channel 3 of the output fibers at 10 μm in the axial direction (the X-axis as shown in figure 1) and carries out the light tracing processes in the radial direction (the Y-axis and the Z-axis as shown in figure 1) until the insertion loss is below 2 dB. Then, the input fiber is switched to channel 4 to carry out the light tracing processes until the insertion loss is below 2 dB, too. By the same process steps and method, the input fiber switches and aligns channels 1 and 2 of the output fibers. The light tracing process is completed and stopped when the insertion loss of all four channels is below 2 dB. Therefore, these alignment steps and the method for the 1 × 4 optical switch may be repeatedly run for many times. When the losses of all four channels of the 1 × 4 switch are below 2 dB, we package module-1 and module-2 with UV glue. A 1 × 4 mechanical optical switch has successfully been completed after running the initial 100 times cycle test and the long-time reliability test. A photo of a 1 × 4 mechanical optical switch is shown in figure 12.



(*a*)

(*b*)

(*c*)

(*d*)

Figure 14. The ch1 to ch4 insertion losses of the 10 000 cycle times test: (*a*) the insertion loss of ch1, (*b*) the insertion loss of ch2, (*c*) the insertion loss of ch3 and (*d*) the insertion loss of ch4.

6. Experimental results

The optical fibers in use have the following specifications: multi-mode fiber, outer diameter 125 μm, core diameter 62.5 μm, non anti-reflection coating and no cut angle of the fiber end tip. According to the BELLCORE 1073 specifications, the insertion loss of a 1 × 4 optical switch has to be below 2 dB [17]. The switch has to be subject to a test run of 100 cycles after it is aligned and packaged; the best results of the insertion loss are ch1: 0.68 dB, ch2: 1.49 dB, ch3: 0.71 dB and ch4: 0.97 dB, respectively, as shown in figures 13(*a*)–(*d*).

In order to demonstrate the long-time reliability, with the insertion loss still being below 2 dB after a long run, the switch is subject to a further test run of 10 000 cycles. The best results of the insertion losses of the four channels are ch1: 1.67 dB, ch2: 1.63 dB, ch3: 0.75 dB and ch4: 0.98 dB as shown in figures 14(*a*)–(*d*). The results have been checked and found to comply with the BELLCORE specifications.

7. Conclusions

By adopting the fiber-to-fiber configuration as the optical path transmission type, a miniature, low cost and highly reliable 1 × 4 mechanical optical switch has successfully been developed. Its size is only 20 × 20 × 25 mm^3 and the structure is the simplest among all existing 1 × 4 mechanical optical switches. The experimental test results show that after an initial 100 cycles test run the insertion losses of the four channels are ch1: 0.68 dB, ch2: 1.49 dB, ch3: 0.71 dB and ch4: 0.97 dB; the switching time is 5 ms, the crosstalk <80 dB. The reliability tests of the insertion losses of the four channels after 10 000 cycles are ch1: 1.67 dB, ch2: 1.63 dB, ch3: 0.75 dB and ch4: 0.98 dB. Its size and cost are about 1/5–1/10 and 1/10 of the series-connect and prism-type switches; moreover, compared with the MEMS type, this novel switch is only about 1/20 of the today's cost. In future, we will apply the automatic light tracing alignment (ALTA) technique developed by us, to speed up the alignment and packaging process for mass production and to reduce the difference of the insertion loss of the four channels to below 0.1 dB.

Compared to other types of 1 × 4 mechanical optical switches, which dominate the market, our switches have the following advantages:

1. The size of our switch is 10 times smaller and the cost is only 1/20 of the cost of other types of 1 × 4 mechanical optical switches. In addition, the mechanism of actuators is the simplest due to the adaptation of fiber-to-fiber configuration.
    (a) Compared to the series-connection-type switch, which comprises three 1 × 2 switches, for example, the 1 × 4 switch of the Lightwave-link Co. (18 × 76 × 76 mm^3), our switch is only about 1/11 of their size and 1/5–1/10 of their cost.
    (b) Compared to the prism-type switch, which uses prisms as reflection components to change the optical signals path, as the 1 × 4 switch of the DiCon Co. (70 × 50 × 14 mm^3) for example, our switch is only about 1/5 of their size and 1/10 of their cost due to the omission of expensive optical components.
    (c) Compared to the MEMS-type switch, which uses micro-mirrors to reflect optical signals, as the 1 × 4 switch of the MEMSCAP Co. (76 × 76 × 14 mm^3) and AOMEMS Co. (138 × 51 × 25 mm^3) for example, our switch is only about 1/8–1/17 of their size and 1/10–1/20 of their cost, due to the dispensable need for expensive equipments and high product development cost.
2. Our switch lowers the minimum limit of the 1 × 4 switch insertion loss to 0.346 dB because it uses a fiber-to-fiber configuration that allows a one-time transmission through the fiber–air–fiber interface, whilst in the case of the series-connect-type switch the transmission through the fiber–air–fiber interface occurs twice and the minimum insertion loss is thus 0.692 dB. The optical fibers in use are of the following specifications: no anti-reflection coating, no index-matching oil and zero angle of fiber end tip. Therefore, our switch has a lower limit of the insertion loss compared to the series-connect-type switch. In addition, it does not include the connection loss between two 1 × 2 optical switches.
3. Using traditional machining technology and the two stages geometry error reduction principle, the precision for the input fiber switching position can reach the micro/nano degree, namely to about 0.27 μm.
4. It is possible to achieve mass production of 1 × 4 switches by applying the automatic light tracing alignment (ALTA) technique developed by us, to speed up the alignment and packaging process for the 1 × 4 switches, and to reduce the difference of insertion losses of the four channels to below 0.1 dB. This has the advantages of minimizing the eye damage caused by a long-time manual assembly and alignment and increasing the packaging speed.
5. In future, we intend to use low thermal expansion INVAR steel for the housing (size: 20 × 20 × 25 mm^3) and the ANSYS software analysis to compensate for the thermal deformation encountered during a sharp thermal gradient (not detailed in this report, please refer to [18]). This structure is made to suit hostile environments.

Acknowledgments

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