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A miniature low cost and high reliability 1 × 2 mechanical optical switch

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Abstract
This paper presents the design, fabrication and tests of a miniature 1 × 2 mechanical type optical switch, whose components are fabricated by precision machining and MEMS technologies. The packaging and alignment are integral processes utilizing the CCD image processing technique and PZT-stages controlled technique in association with the optimization software enabling the fiber-to-fiber alignment to low optical loss requirement. Optical fibers in use have the following specifications: single-mode fiber (SMF) outer diameter 125 μm, core diameter 9 μm, zero degree of the fiber tip angle and non-anti-reflection coating. The initial gap of the input and output fibers is 10 μm. First, we produced a fiber holder and a V-groove by MEMS technology and used a relay as the input fiber switching actuator. Through proper mechanism design, the fiber positioning error can be reduced to below 0.1 μm. After the optimized alignment process, the results presented that the insertion loss could be controlled to ch1: 0.8 dB, ch2: 1.4 dB at a switching time of 5 ms. The reliability tests demonstrated that the variation of the insertion losses are ch1: 0.04 dB, ch2: 0.02 dB after 10 000 cycle times, and ch1: 0.024 dB, ch2: 0.006 dB throughout 100 switch times after 1 000 000 cycle times. The developed 1 × 2 optical switch largely reduces the physical size to 1/2–1/3 in comparison with traditional mechanical optical switches, and the cost is only about 1/10–1/20 of the MEMS type optical switches. The advantages of this innovative optical switch are: small size (only about 20 × 16 × 7.5 mm^3), low cost (only about US$10), high reliability, cross-talk ≦ −80 dB and automatic alignment.

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

1. Introduction

The popularization of the Internet and personal communication leads to huge demand for an optic fiber network doubling its growth every nine months on average. The technology of DWDM (dense wavelength division multiplexing) enables the coupling and transmitting of signals of different light wavelengths in one single fiber. Therefore, it can easily boost several dozen to hundred times the capacity of transmission of an optic, and it is the best way to expand the bandwidth of a network. If the fiber optic communications network is treated as a highway, the data flow being analogous to the traffic flow, then DWDM can be regarded as an increase of the road width (namely the bandwidth of the network). In a case where the distribution between the data flow and bandwidth is poor, it will cause a bottleneck for communication. Therefore, it needs the component of the optical switch to make the best use of DWDM as the moderate distribution of 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. Future trend will focus on the signal switch in the optical domain at the node, path protection and add/drop accessibility in order to increase the processing speed and maintain optical transparency. Hence, the population of optical switch is one of the keys to the future DWDM network development. Conventional optical switches used optic–electro-optic (O–E-O) type [2]. In this type, optical signals from the input fiber will firstly convert to electronic signals, which then through an electronic converter switch to the required output channel. Passing through an EO converter, the output optical signals can then couple to the output fiber. The devices of this type, however, have several drawbacks. For example, they require expensive optic–electro conversion devices. Insertion loss and cross-talk are usually high. Also, the electronics bottleneck constrains the growth in the capacity of optics for further bandwidth demand. The all-optic (optic–optic–optic, O–O–O) switching design is potentially capable of eliminating these disadvantages [3]. Consequently, it is suitable for the next generation of the optical switching technology.

Concerning the O–O–O types of the optical switch, the mechanical type still dominates the market. The proportion of various mechanical types of optical switch is around: prism type 84%, MEMS type 7% and moving-fiber type 9%, respectively [4]. Although they are all efficient and available in the market, from the size and cost consideration, however, there is still some room to improve. This study has developed the smallest and cheapest 1 × 2 mechanical type optical switch. Its physical dimensions are only 20 × 16 × 7.5 mm^3 and its direct cost is only about US $10. Compared to some existing prism types, such as the DICON 1 × 2 optical switch (size 67 × 23 × 16 mm^3) and JDSU 1 × 2 optical switch (48.36 × 18.14 × 8.86 mm^3), this miniature innovated optical switch is about 1/3–1/10 of their sizes. Moreover, due to the elimination of expensive collimators and prisms, the direct cost of this new optical switch can be reduced to about 1/5–1/10 order. Although the MEMS type has similar feature of small size, such as DICON 1 × 2 (20.83 × 12.7 × 7.21 mm^3), it needs complicated and expensive fabrication equipment. Our optical switch costs about 1/10–1/20 relatively. For the moving-fiber type of current optical switch, such as the Hitachi product (with size of 28 × 15.6 × 8.3 mm^3), our size is about 2/3 and cost is around 1/5–1/10 comparatively.

The characteristics of these types are to switch data flow without optic–electro (O–E) conversion. As the optic fiber network system is getting more complicated, many traditional mechanical types of optical switches are unable to meet the requirements of growing capacity and the BELLCORE standards, especially in the cost consideration. Hence, it is a future inevitable trend to overcome the bottleneck of the so-called 'last mile' by using the micro/nano precision technologies for developing new generation optical switches. The said micro/nano technologies may include precision machining, MEMS fabrication, micro packaging and fiber alignment with PZT stages and precision metrology.

2. Design of a mechanical 1 × 2 optical switch

There are several types of optical switches, such as traditional mechanical prism optical switches [5], MEMS optical switches [6], liquid crystal optical switches [7], acoustics-optic optical switches [8], holographic optical switches [9], thermal-optics optical switches [10], etc. They could all meet the requirements from the fundamental theories. In practice, however, optical switches have to adapt to various environments, especially the ambient changes. All year round, all parts are deformed because of the non-uniform temperature conditions. It causes the misalignment of optical axes between the input fiber and output fibers. In this study, not only the precision packaging and alignment tasks have to be coped with, but also the stability due to temperature change is an important issue to be considered in the switch design. Some design aspects are addressed in the following.

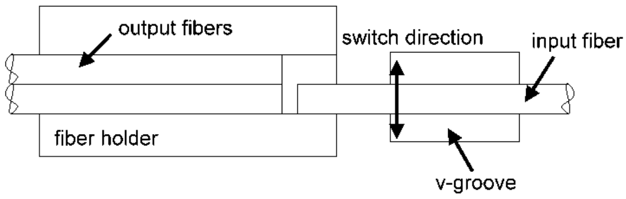

Figure 1. Fiber-to-fiber switch configuration.

2.1. *Design principles of the switch mechanism*

A novel 1 × 2 micro/nano mechanical optical switch is designed which is based on the direct fiber-to-fiber principle, as shown in figure 1. For structural simplicity, low cost and low power consumption, this design eliminates some conventional parts, such as the collimators, turning mirrors and prisms [11]. The input fiber is mounted onto a V-groove and switched by a simple mechanical relay, and the output fibers are firmly held by a fiber holder. Both the V-groove and the fiber holder can be fabricated by a MEMS process in order to ensure its accuracy.

There are several advantages of this novel design: (1) compared to the traditional optical switches, it omits the collimators and prisms so as to reduce the device size and cost, (2) the MEMS fabrication process for the V-groove and the fiber holder is easy and of low cost, (3) the direct fiber-to-fiber configuration needs only the near field co-axial alignment technique, which promises less optical loss than other light bending configurations, (4) simpler configuration yields to easier assembly process to high precision, (5) employing computer- and image processing-aided alignment processes the throughput can be faster, and (6) use of the low thermal expansion INVAR steel for the housing (size: 20 × 16 × 7.5 mm^3) and ANSYS software analysis to compensate for the thermal deformation (not detailed in this report; see [12]). This structure is sturdier to suit various environments. The mechanism design of this novel optical switch is illustrated in figure 2.

2.2. *Design of actuator*

We use an industrial miniature relay (14 × 9 × 5 mm^3), made by Omron Co, as the actuator to switch the input fiber to required positions. Figure 3 shows the switching principle. The switching time of relay can be made within 10 ms. It can be seen from figure 1 that the side walls

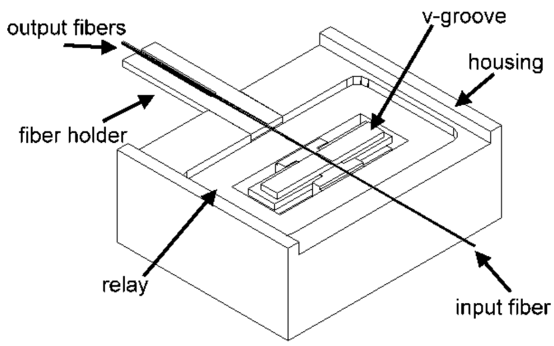

Figure 2. Micro/nano 1 × 2 optical switch.

of the fiber holder (12 × 3 × 0.5 mm^3 with U-groove of 125 μm in depth and 250 μm in width, as shown in figure 3) play the role of a stopper of the switching input fiber. From the parameter design of the switching mechanism, the variation of the correct positioning of the input fiber can be significantly reduced to about ten times by the stopper based on the lever design. In addition, using finite element analysis to design the dimensions of all components, the optimized elements with material selection for thermal compensation can theoretically yield a misalignment error below 0.314 μm under environment temperature change from 70° to –5 °C [12]. The final fiber-to-fiber positional thermal drift can be fully compensated. This paper does not describe detailed design analysis of this part.

2.3. Error reduction of switch mechanism

The mechanical relay has inherent switching error of positioning with the amount of about 10 μm at the end point (δp), as shown in figure 4(*a*). Based on the lever principle this amount can be reduced to 2 μm at the end point of the y-arm (δ_f), which is the location of the V-groove. Again, as shown in figure 1, the V-groove positioning error can be further reduced to below 0.1 μm after the second trigonometric relationship of the fiber stopper pivot mechanism. As shown in figure 4(*b*), if there is no stopper in the fiber holder, the lateral misalignment δ_2 ($=\delta_f$) of the input fiber will cause the same amount to the output fiber because it is straight and parallel. The effectiveness of the stopper acts like a second lever mechanism and, due to the ratio of arms (a/b about 1:10), the lateral misalignment could be significantly reduced in proportion.

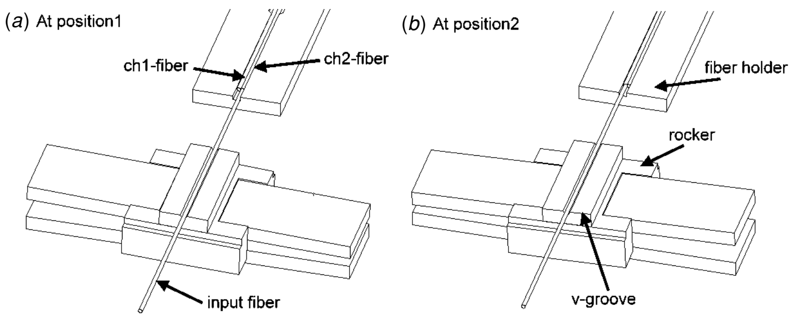

Figure 3. The switching mechanism.

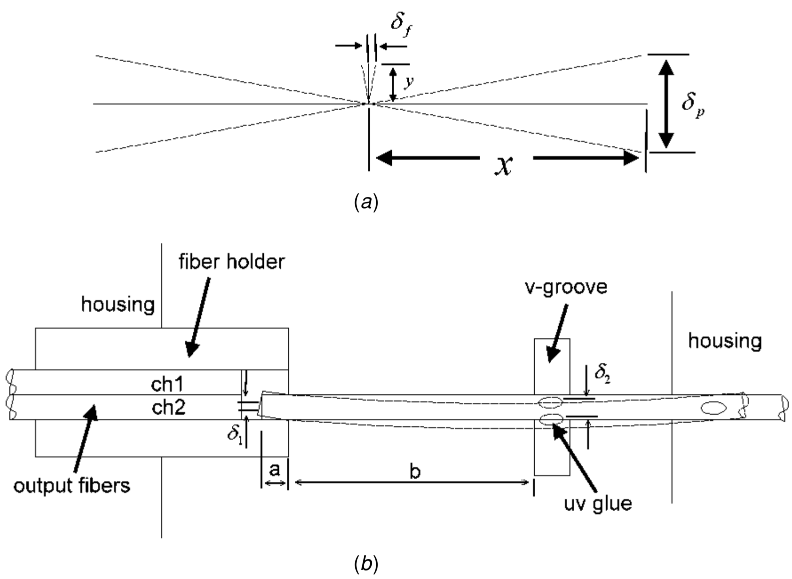

Figure 4. Principle of geometrical error reduction.

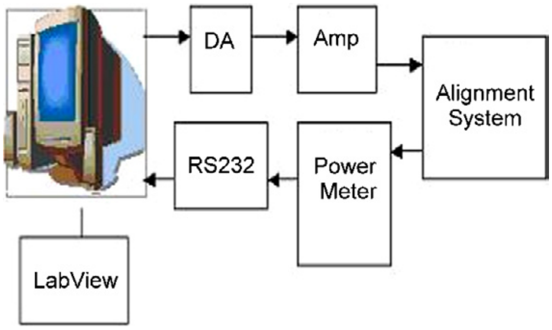

Figure 5. Block diagram of the alignment system.

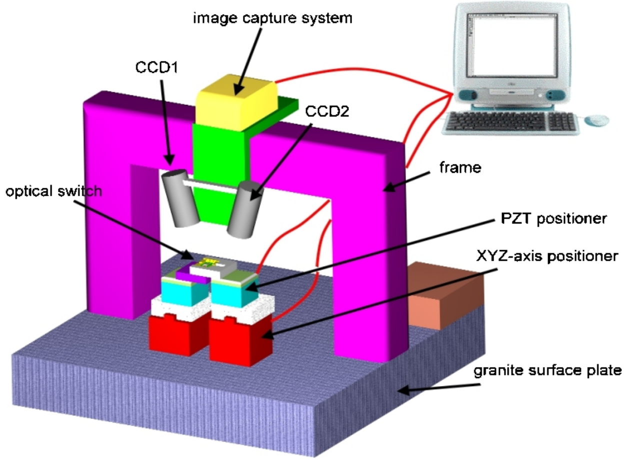

Figure 6. Experimental set-up of packaging and alignment processes.

3. Computer-assisted automatic alignment system

Optical fibers in use have the following specifications: single-mode fiber (SMF) outer diameter 125 μm, core diameter 9 μm, zero degree of the fiber tip angle and non-anti-reflection coating. The initial gap of the input and output fibers is 10 μm. The initial fiber-to-fiber alignment is a difficult task that must allow two output signals strong enough to meet the BELLCORE specifications. Manual work is laborious and subject to harm the eyes. This study developed the CCD image processing technique in association with two sets of six-axis PZT stages to achieve this goal. The system block diagram is shown in figure 5. The alignment system consists of a 1550 nm laser source, an optical switch, an image system, two six-axis PZT stages and an optical detector. The image system detects the initial fiber-to-fiber position to about 10 μm in the axis alignment. The optical detector outputs its signals to a power meter through an RS232 serial port to the PC. Applying the developed LABVIEW software, the PC can output analog signals via a D/A converter to drive the PZT stages so as to adjust the fiber positions. The optimization software installed in the PC is then activated to fine tune the stage positions

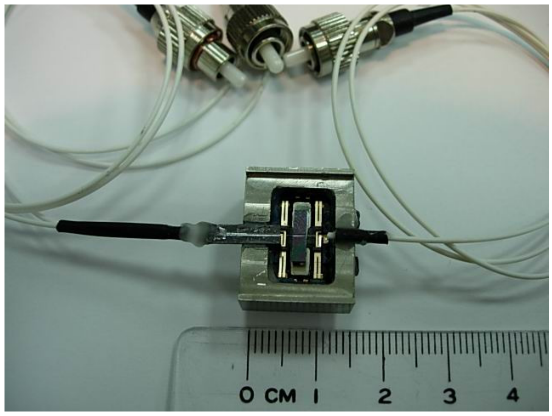

Figure 7. Photo of the developed 1 $\times$ 2 optical switch.

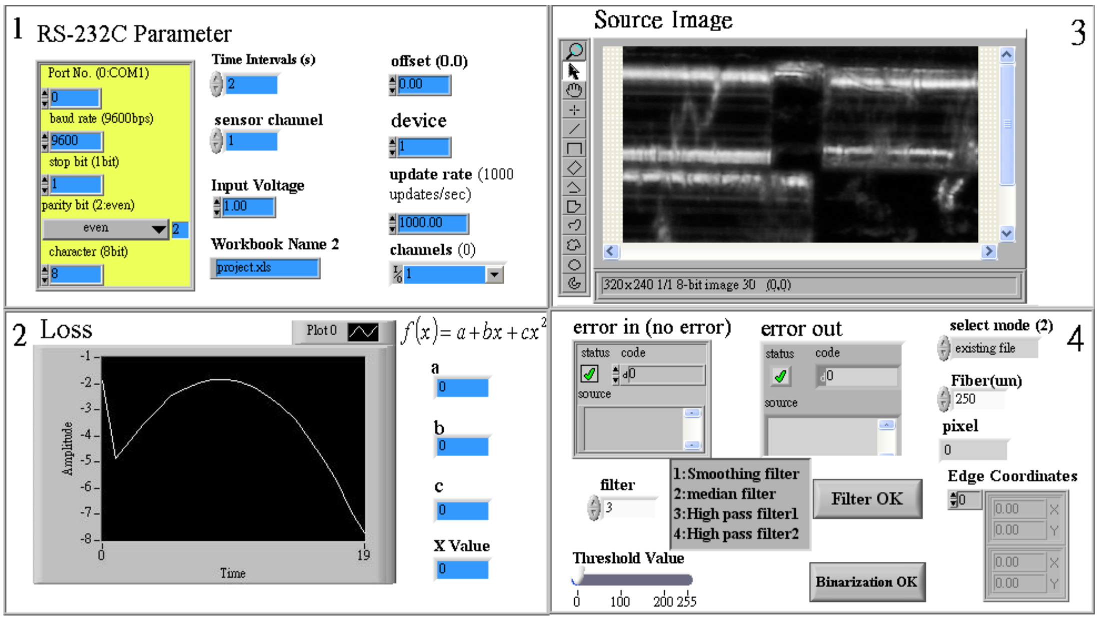

Figure 8. Screen of real time display.

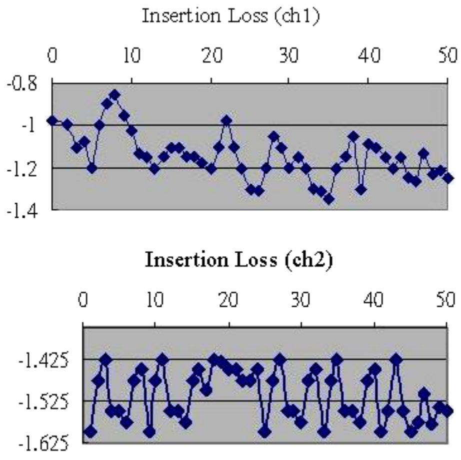

Figure 9. Insertion loss tests of ch1 and ch2.

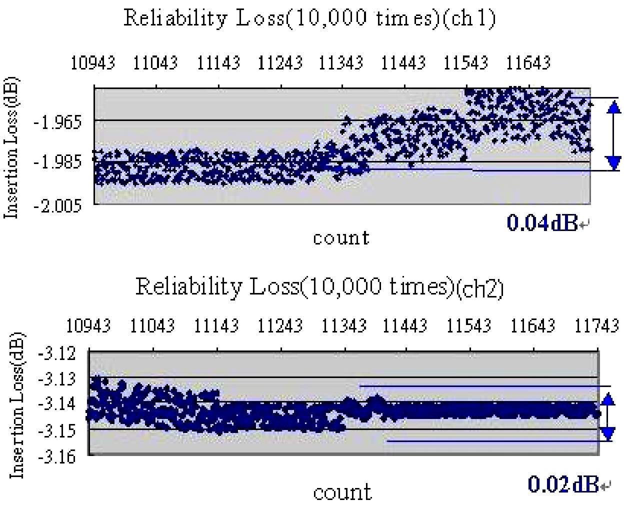

Figure 10. Reliability test of ch1 and ch2 during 10 000 cycle times.

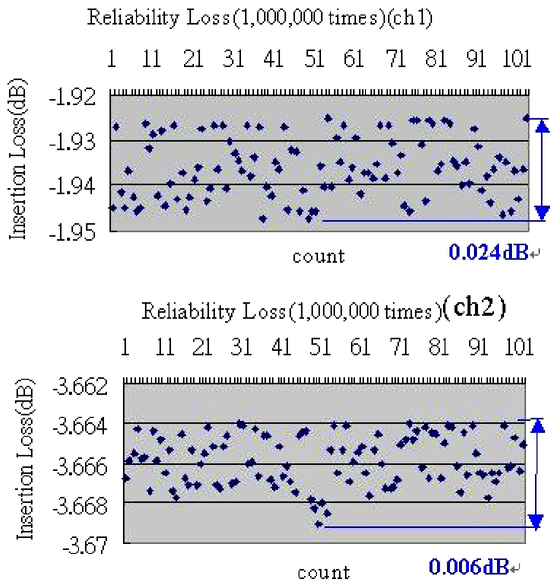

Figure 11. Reliability loss of ch1 and ch2 after 1 000 000 cycle times.

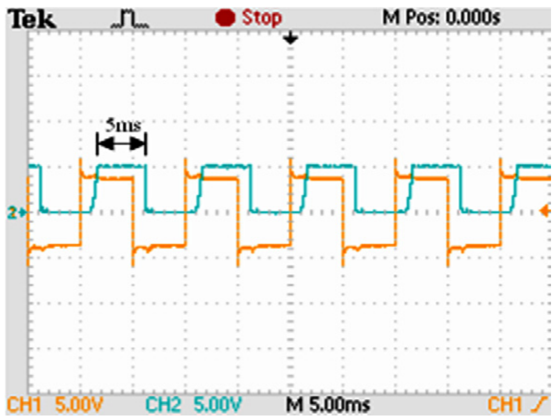

Figure 12. On/off responses versus the switching time.

so as to minimize the optical loss during switching. During the assembly process, the fiber holder module (consisting of fiber holder and two output fibers) and the housing module (consisting of the input fiber, relay, V-groove and housing) are operated to align the light. The insertion loss between ch1 and ch2 will by all means be affected by the dimension accuracy and roughness of the fiber holder. The actual positions of ch1 and ch2 will be slightly deviated from their ideal positions. Therefore, using the CCD image and PZT stages to control the light search program in order to achieve the minimum insertion loss is a dynamic and optimum means. Finally, the UV glue is used to adhere and fix the fibers [13] to accomplish the alignment and package processes of the 1 × 2 optical switches. Figure 6 shows the experimental set-up of the developed automatic packaging and alignment system. Figure 7 shows the picture of the developed miniature 1 × 2 optical switch whose physical dimensions are only 20 × 16 × 7.5 mm^3.

This study utilized the LABVIEW software as the system-developing tool. During the alignment and reliability tests, some real time information can be viewed. There are four areas displayed on the PC screen, as shown in figure 8. The first area lists the controlled parameters including voltage, time and channel. The second area displays the optical loss diagram, which is used to feedback control the PZT stages to compensate the errors. The third area displays the captured fiber-to-fiber image. The fourth area displays the parameters of image processing, such as threshold for image binarization, intensity enhancement and filtering. The alignment process is conducted by two stages for position adjustment: the rough stage by CCD detection and the fine tune stage by optical signal output.

4. Reliability tests

After the packaging and alignment processes were completed, the reliability tests were carried out. The complete system was placed in a mini environment chamber in which the temperature and humidity can be computer controlled. The goals are to test the insertion loss (IL) and long time reliability loss (RL). Setting a constant temperature of 22 °C and humidity of 50%, figure 9 shows that the best insertion loss of ch1 is 0.8 dB and ch2 is 1.4 dB with the switching time of 5 ms for a 50 min run. Figure 10 shows the insertion loss after the fiber holder module and the housing module have been UV glued and solidified. The initial insertion losses are: ch1 = 1.97 dB and ch2 = 3.14 dB. As compared to the best insertion losses as given in figure 9, extra insertion losses due to this packaging process are found with ch1 = 1.17 dB and ch2 = 1.74 dB. This is a reasonable phenomenon [14, 15] and should be overcome in the future. Figure 10 also demonstrates that the reliability tests of the relative optical losses after 10 000 cycle times are ch1: 0.04 dB and ch2: 0.02 dB. After 1 000 000 cycle times, the relative optical losses throughout 100 switch times are ch1: 0.024 dB, ch2: 0.006 dB, as shown in figure 11. The insertion losses are all slightly larger than the allowable value of 1 dB as specified by the BELLCORE standard. It is because the current fibers in use are all non-anti-reflection coated and non-8-degree edge cut at the tip. The equipment for those processes are expensive and are not affordable by us. It is believed that after these processes the final insertion loss could fall into the BELLCORE requirement. However, the stability of long time reliability tests has shown very promising results with only a very small amount of optical loss variation. Figure 12 shows the wave forms of the switching time.

5. Conclusions

Utilizing the micro/nano technologies, a miniature mechanical type 1 × 2 fiber-to-fiber optical switch has been developed successfully. The switch size is only 20 × 16 × 7.5 mm^3. Its structure is simpler than most of the existing optical switches. Experimental results showed that, for single mode fiber-to-fiber alignment with coarse and fine stages, the insertion loss could be controlled to ch1: 0.8 dB, ch2: 1.4 dB with switching time 5 ms, and cross-talk ≦–80 dB. The reliability tests demonstrated that the variation of the insertion losses are ch1: 0.04 dB, ch2: 0.02 dB after 10 000 cycle times, and ch1: 0.024 dB, ch2: 0.006 dB throughout 100 switch times after 1 000 000 cycle times. The developed 1 × 2 optical switch largely reduces the physical size to 1/2–1/3 in comparison with traditional mechanical optical switches, and the cost is only about 1/10–1/20 of the MEMS type optical switches. The advantages of this innovative optical switch are small size, low cost, high reliability and automatic alignment.

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