Large Core Diameter POF/PCF Optical Switch Using Shape Memory Alloy (SMA) Coil Actuator for Local Area Network (LAN) System

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***Abstract*—The polymer optical fiber (POF) is mostly suitable for house held optical switches because of its large core diameter. A high performance optical switch building process is described. In order to achieve high performance switching and low data loss, we examine different technique while building different parts. Furthermore, we show the comparison of surface roughness of POF/PCF using different processing methodology to minimize the optical insertion loss. This research developed a fiber fixing Jig for Mechanical polishing method, and we discovered that, the Mechanical polishing method able to provide 1/3 (0.08 dB) optical insertion loss than the Mechanical cutting method. Another challenge was to build the main structure of the switch, and how to Seal inside's matching oil properly. As long as, our target is to build a low-cost switch, we selected an acrylic substrate for the body. Switching speed is less than 0.5 second, and the insertion loss of the fabricated switch is 0.4 to 0.5 dB. The insertion loss is 0.06 to 0.09 dB when using index-matching oil.**

***Index Terms*—LAN, POF, PCF, optical switch, SMA coil, mechanical polishing, standby network**

I. Introduction

For office and home environment Polymer optical fiber (POF) is more suitable than the all glass optical fiber to construct LAN (Local Area Network) [1]-[3], because of its flexibility and ease of connection by relatively large core diameter. Indoor local area network (LAN), for example, in-home or office networks, plastic optical fiber (POF) is more suitable than silica optical fiber because of its flexibility and large core diameter (e.g., 0.486 mm), which facilitates connection [4]. If the information network is likened to a bloodline, the All Glass Fiber (AGF) which is used in the public telephone network would be the main artery and PCF/POF which transmits communication to the home and office would be the capillary tube [5]. Fig. 1 shows a comparison with data transmission rate vs distance with AGF, PCF and POF. Also comparison to AGF, PCF, and POF are:

(1) Applied to economical optical module, because of its high NA, can be conjunction with low cost optical module.

(2) Can be easily assembled by use of crimp & cleave type optical connectors. In a system using many optical modules and optical connectors, PCF/POF is a good cost alternative over AGF for the instillation of optical cable in the system.

POF (Polymer Optical Fiber) and PCF (Polymer Clad Fifer) is more suitable candidate for indoor LAN (Local Area Network), for example in-home or office networks because of its flexibility and ease of communication by relatively large core diameter [4], [6].

As a standby network system for emergency situation, or to expand the network system 1×2 POF/PCF optical switches will be very useful for indoor LAN system [7]. But the main concern is optical power loss due to the roughness of fiber tip surface. This paper will introduce the method of fiber tip surface preparation, and fabrication of optical switch using POF and PCF. To shape the main body of the optical switch, we used high speed milling machine with high accuracy. We will describe about the high speed milling machine and how it can shape materials.

In order to fabricate optical switches with low insertion loss, we have tested several types of fiber end face processing. The best one we have selected for this optical switch will be described.

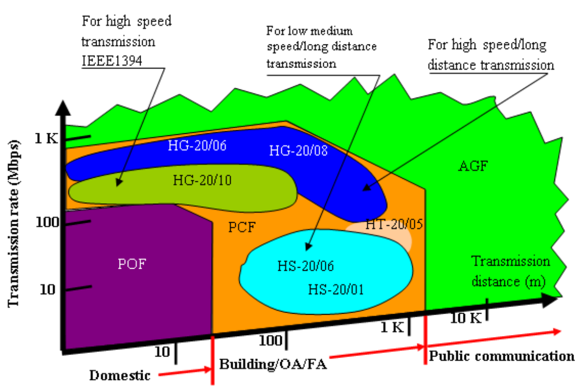


Figure 1. Transmission rate vs distance comparison of AGF, PCF and POF [5].

Manuscript received December 30, 2013; revised May 6, 2014.

2015 Engineering and Technology Publishing
doi: 10.12720/jiii.3.1.26-31

II. Structure and Principle of Switch

A suitable structure of the optical switch is shown in Fig. 2. There is a Polymer optical fiber (POF) fixed to a SMA coil inside the switch and another two POF are attached in the outside the switch. The switching mechanism is built such a way that at a time one of the outer side POF will align with the inside optical fiber.

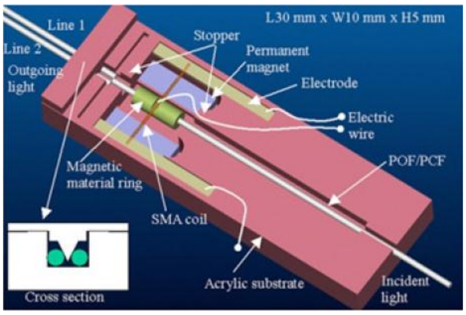


Figure 2. Design concept of POF/PCF switch.

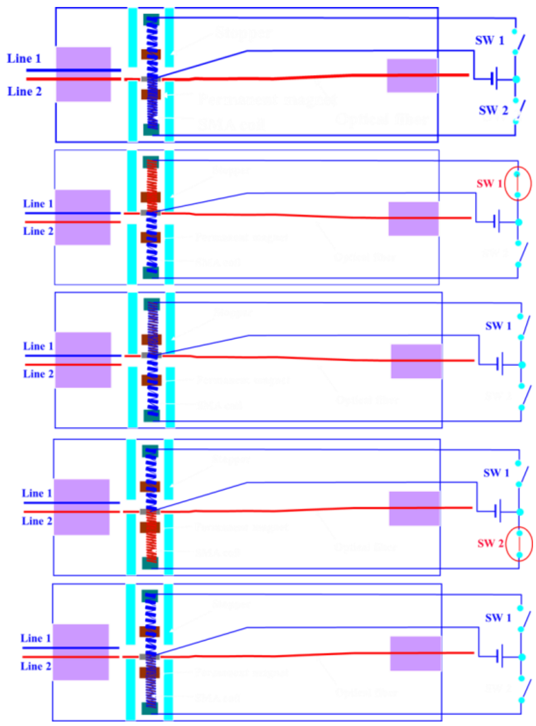


Figure 3. Switching mechanism.

If SW1 in Fig. 3 is turned on, electrical current is applied to upper half of the SMA coil and the upper half of SMA is heated above a certain transition temperature by direct heating and contracts. POF, which is attached to the SMA moves towers upper side and the light is passed into the upper left side POF. If SW2 is turned on similarly, the same change will be occurred in the lower SMA and the POF is moved lower side. For switching by movement of a POF, large displacement is needed because of large core diameter (in this case, Core diameter: 0.486 mm, Outer diameter: 0.5 mm) and this device needs displacement of 0.5 mm. It is relatively difficult to get displacement of 0.5 mm by micro actuator for example, electrostatic actuator, piezoelectric actuator etc. We chose SMA coil actuator for large displacement.

III. Fabrication Process

A. Processing of POF and PCF End Surface

Smooth POF and PCF ends are necessary to minimize the insertion loss. Many types of POF end face processes have been reported. Hot plate process, hot knife cutting process, cold cutting process (in this paper called knife cutting process), mechanical cutting process, manual polishing process, and mechanical polishing process are under considering for POF end process. In this report I would like to describe all of those processes and will mentioned both negative and positive characteristics.

1) Types and processes of POF and PCF end

- Hot plate process

The Hot Plate Termination method, which Mitsubishi Rayon put forward, is the popular termination method. Utilizing the material characteristics (End face of fiber) is heated till soft. Then the end face is pushed toward a plate to transfer the mirror face to the fiber end. The Hot plate technique is a very quick process and no special skills are required. But, high temperature generates bubbles and increases insertion loss. Another problem is of the Hot Plate process is that the share of the edge of POF ends changed. This shape could cause angular misalignment for our optical switch.

- Hot knife cutting process

This process is also an easy process, but usually a hot design knife is used for this process, the surface of the POF end cannot be made very smooth. The insertion loss is larger than the hot plate process.

- Cold knife cutting process

This process is also an easy process, but usually a design knife is used for this process in at room temperature. The surface of the POF end is larger very rough, and the insertion loss make larger than of the Hot cut process as shown in Table I.

TABLE I. Process of Fiber End and its Characteristics

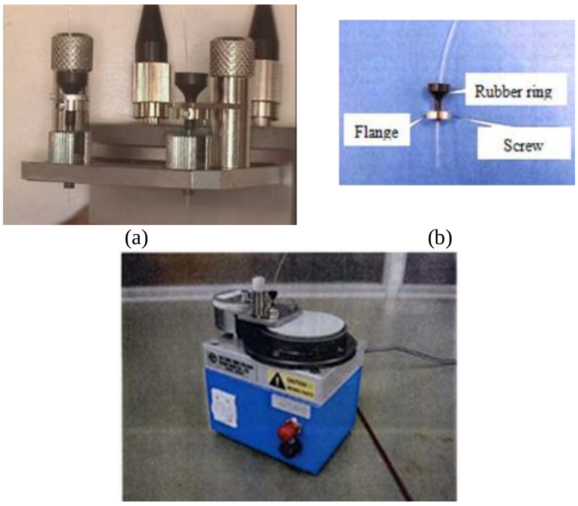
Process	Insertion Loss	Reproducibility
Mechanical Polishing	~1dB	◎
Hot Plate	~1.5dB	○
Hot Knife Cutting	~2dB	△
Knife Cutting	~3dB	×

- Manual polishing process

After cutting the POF by design knife, a manual polishing process was tested. Several polishing sheets with difference roughness were used for this method. The roughness of polishing sheet ranges from high to low. Its workability is not good but the insertion loss is comparatively lower than the knife cutting process. Reproducibility of this process is not good.

- Mechanical cutting process

We have tested a mechanical cutting process using POF cutting tool. POF end will be processed by a rotted blade. The POF end is smooth comparatively before mentioned process. But, any one side of POF face cannot make the same smooth surface. To get a low insertion loss, we have tested the mechanical polishing process.



(a) (b)

(c)

Figure 4. Temporary fixing Jig of fiber polishing, (a) Large view of developed Jig, (b) Fiber fixing, (c) Fixed Jig.

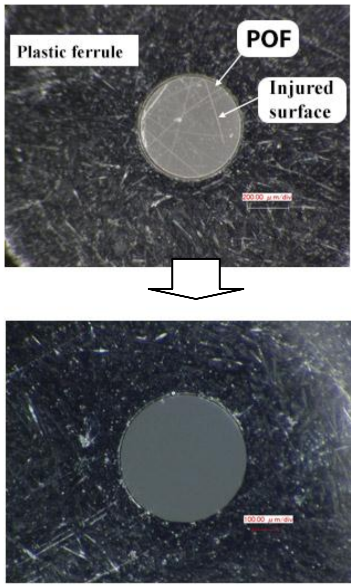
2) Problem and solution of mechanical polishing

To polish the fiber end, we have used mechanical polishing method as mentioned before. To use this method, fiber fixing is necessary by FC connector as shown in Fig. 4(b). But in our fabricating switch, there are two fiber ends for each fiber. Fiber end 1 is inside of the switch where movable fiber and outgoing fiber is faced each other, FC connector is not used. For outside fiber of the switch, fiber end 2 that will connect to power source or power meter, FC connector was used. An adhesive is needed to fix the FC connector to the optical fiber. Any permanent fixing method cannot possible to use at fiber end 1. We have tried several times to polish using tape for temporary fiber fixing, but the result was not satisfied. The results reproducibility was not stable. To solve this problem a mechanical Jig is necessary, which could fix the fiber temporarily.

This research team have consulted with Seiko Giken Co. Ltd. and made a Jig, which can fix the fiber without any adhesive. As shown in Fig. 4 (b), the fiber is transmitted in the rubber ring, and the screw from the outside tightens it. In order to polish the fiber with vertically, a ferrule was used under the flange. A material nut was used for fixing the ferrule. In the stopper, a spring was utilized for exerting a fixed force (30 g) to the downside of the optical fiber. Using this method, we have got an excellent smooth surface of POF and PCF fiber.

3) Optimization of polishing condition

The mechanical polishing machine was used for only silica fiber polishing. For plastic fiber polishing, there was no record or condition previously. In order to optimize the stable surface of plastic fiber with stable insertion loss of optical switch, polishing condition should be decided. According to the maker's suggestion we have done mechanical polishing for silica fiber with zirconium ferrule. The process was, GA07 for 60 sec without water, DM07 for 30 sec without, and SF07 for 30 sec with water. For plastic fiber with plastic ferrule polishing, the mentioned process was not appropriate. As materials were all plastic, the abrasion of the ferrule with fiber was intense by the polishing because polishing time was long. Furthermore, the polished fiber face was not smooth as shown in Fig. 5(a), because water cleaning was not sufficient for every process.



(a)

(b)

Figure 5. POF end surface after polishing, (a) Water used only for finishing process, (b) Water used for every process.

In order to solve this problem, the polishing time and cleaning condition were considered in this study. We decrease the polishing time and used water to get a smooth surface of optical fiber for every polishing process. Finally, we got a smooth surface of POF as shown in Fig. 5(b), and its reproducibility was good.

TABLE II. MECHANICAL POLISHING CONDITION OF POF AND PCF END

Polishing Sheet	POF	PCF	With Water
	Time (sec)		
GA 07	30	45	O
DM 07	30	30	
SF 07	30	30	

Furthermore, PCFs core is silica, so the polishing time is comparatively long for PCF at the first process GA07. Polishing time is not sufficient of PCF. The optimized polishing condition for POF and PCF are shown in Table II. Mechanical polishing method gives us stable smooth surface and its reproducibility was better than other techniques.

B. Main Body of Optical Switch

There are many reports on MEMS optical switches, which used Silicon substrate [8]-[9]. In order to shape vertically, several etching processes are needed. For these reasons, fabricating cost becomes higher. The other hand, the target of our research is a low-cost switch with low insertion loss. An acrylic substrate was selected for main body of our optical switch. In future it will be shifted to the injection and press molding process for high accuracy with low cost. Injection and press molding process are commercially used to make connectors mold (body) [10].

1) Fabrication method of main body and v-shaped caps

A high-speed milling machine (F-MACH) was used for cutting the acrylic substrate. 2.5 dimensional shaped structure is possible to make using F-MACH with high accuracy. An input program operates f-Mach automatically. Program writing software (Feature CAM) was used for programming. To write the program, a drawing will be needed. It is possible to insert a drawing directly from Auto-CAD to the Feature CAM. Another way is possible to write drawing directly in Feature CAM.

To operate the F-MACH, before the processing of main body of switch, appropriate tools and processing conditions were chosen and checked using a simulator as shown in Fig. 6(b). Also to shape a V-shaped cap for alignment of optical fibers is used F-MACH. A simulated photograph of V-shaped cap is shown in Fig. 6(a).

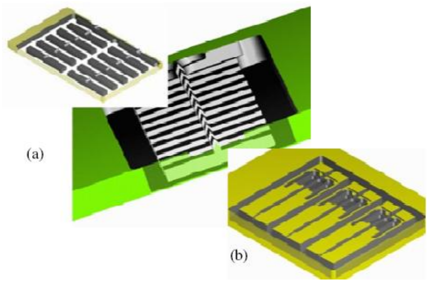
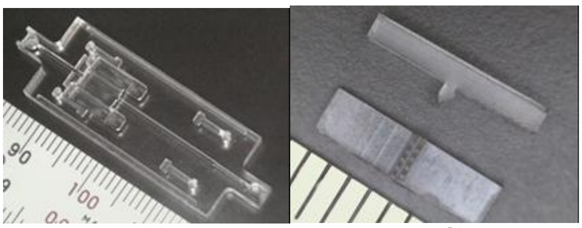


Figure 6. (a) V-shaped caps, (b) Main body

2) Fabricated main body and v-shaped caps of optical switch

The acrylic substrate was cooled by water to avoid deformation during high-speed milling. A V-shaped cap for alignment of optical fibers was fabricated using the same milling machine. The acrylic structures and V-shaped caps were batch fabricated from the acrylic plate. To reduce the dicing process for dividing every chips, a depth drain line around the chips have been done by F-MACH during the milling. After finishing the milling, slightly pressed from the under of substrate, and separated easily. Fabricated parts of optical switch are shown in Fig. 7.



(a) (b)

Figure 7. Optical switch (a) main body (b) V-shaped cap.

3) Assembly process

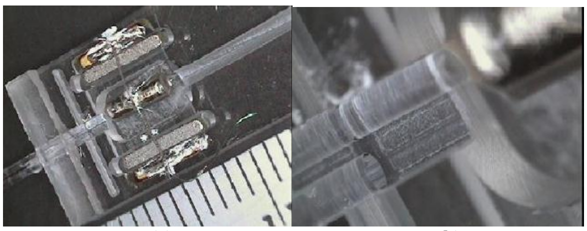
Table III lists the switch parts. The SMA coil, permanent magnet (neodymium magnet), magnetic material ring, and ferrule are bought from Toki Co. Ltd., 26 Magnet Co. Ltd., Japan Mex Co. Ltd., and Sumitomo Shouji Tohoku Japan Co. Ltd. respectively.

TABLE III. DESIGNED ELEMENTS OF OPTICAL SWITCH

Items	Parameter
Fiber	Multi-mode POF (SI type), Core: 0.486, Clad: 0.50 mm, NA: 0.5 Multi-mode PCF (SI type), Core: 0.20, Clad: 0.23 mm, NA: 0.37
SMA coil	Ti -Ni, 0.2 (e.d.) mm × 0.05 (w.d.) mm × 4 (l.) mm
Permanent magnet	Neodymium magnet, 6 (L) mm × 2 (W) mm × 1 (H) mm, flux density: 190 mT
Magnetic material ring	Fe, 1.6 (e.d.) mm × 0.6 (w.t.) mm × 4.0 (l.) mm
Ferrule	Polymer, ϕ 2.5 mm

Above mentioned parts were assembled on the processed acrylic substrate as follows:

- Cu electrodes for driving of the SMA were attached to the substrate with adhesive.
- SMA coil was electroplated by Cu electro less plating for soldering with magnetic material ring and Cu electrodes.
- The middle of the SMA coil was fixed to a ring made of magnetic material and connected to the electric wires (ϕ 60 µm) by solder.
- Out of solder of SMA coil, Cu was removed by etching process.
- The movable side of the POF was inserted into the magnetic ring and fixed using adhesive.
- Two fibers were placed in the grove of the substrate and properly fixed by pressing from upper side using a V-shaped outward extension Fig. 8(a).
- The gap between the opposed POF ends was adjusted under a microscope. The gap was under 50 µm Fig. 8(b). The lateral displacement and angular misalignment was neglected.
- For fixing the fibers were used an adhesive.
- Two permanent magnets were fixed to each predetermined position of the substrate and fixed by adhesive.

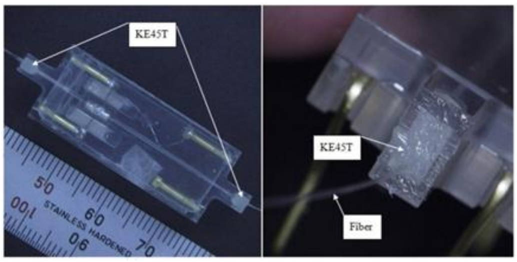


(a) (b)

Figure 8. Fabricated SW (a), Large view of fiber alignment (b)

4) Sealing problem and solution

At movable point of fibers, to protect from mechanical sock we have used flexible silicone two components adhesive (KE106 and CAT-RG) from Sinetsu Co. Ltd. Mixed adhesive was intentioned from the insertion point. After cure by heating, adhesive flowed by the drain of fibers. As a result, fiber has agglutinated by adhesive, and stop moving. We guessed that, during the cure processing the viscosity of adhesive became low. The adhesive in which the viscosity was low by the surface tension seemed to expand. To solve this problem, we considered using different adhesive, which does not needed heat for curing process, and will be quite high viscosity. One component adhesive (KE45T) from same company was selected. By room temperature is sufficient for cure. After curing we have checked flowing condition of adhesive, no major problem was founded as shown in Fig 9(a) and (b). Actuation of packaged switch was confirmed without any difficulty.



(a) (b)

Figure 9. Sealed fabricated SW (a) Top view, (b) Inserting point

IV. Results

In order to confirm the actuation of the optical switch, an optical source (LD) is used into input fiber. A camera is used to catch the changing situation of output fibers. 80 mA current is applied to the SMA coil. SMA coil is moved with movable fiber to the opposite side, and optical light is shifted properly as shown in Fig. 10.

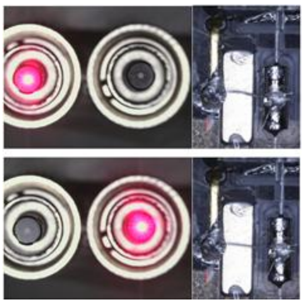


Figure 10. Actuation and Cross-talk test

Insertion loss of fabricated optical switch was less than 0.5 [dB] without using index-matching oil. When index-matching oil was used, insertion loss was less than 0.1 [dB] as shown in Fig. 11. Cross talk was more than –50 [dB] without index-matching oil.

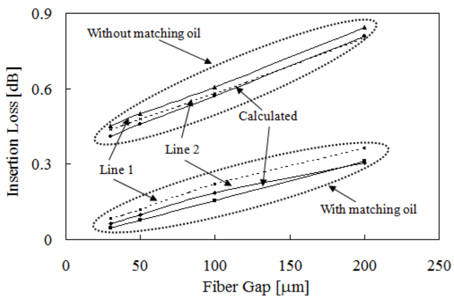


Figure 11. Coupling loss of fabricated optical switch

In this study, a simple stand-by application test [11]-[12] applied to check the performance of emergency trouble. Switching time of emergency situation will be checked to verify for the recovering network system. Some instruments have prepared to determine the recovery time. An application test block diagram is shown in Fig. 12. For this test, two optical switches, which we developed, were prepared. One is to disconnect from PD (850 nm), and another one is for changing a different way. In order to monitor the output of optical power, an oscilloscope is used. A mono stable multi vibrator is used to inform to the SW driver of the optical output signal condition. PCF switch is used for this experiment.

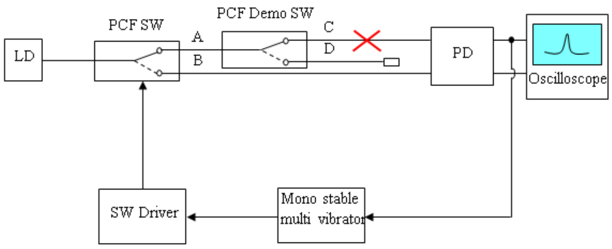


Figure 12. Stand-by switch application for emergency situation

In our experiment, usually optical data will be transmitted by the root of LD → PCF SW → line A → PCF Demo → SW line C → PD → Oscilloscope. Output voltage will be measured by oscilloscope. When the output voltage is sufficient (around 5 V) this period the mono stable multi vibrator will not active. But, once it becomes 0 V (no optical power from LD) then mono stable multi vibrator will be activated. At the same time the driver of SW will change the direction.

Switching speed was less than 500 ms for POF switch, and 260 ms for PCF switch at a driving current 80 mA. In this study, a highest switching speed was measured. At 180 mA, POF and PCF switches speeds are 160 and 80 ms, respectively. PCF's switching condition is shown in Fig. 13. This value is near of commercial optical switch. It can estimate from this result that, in future when it will apply to the single mode fiber switch, this value will become smaller. This speed is sufficient for indoor LAN or short distance network applications.

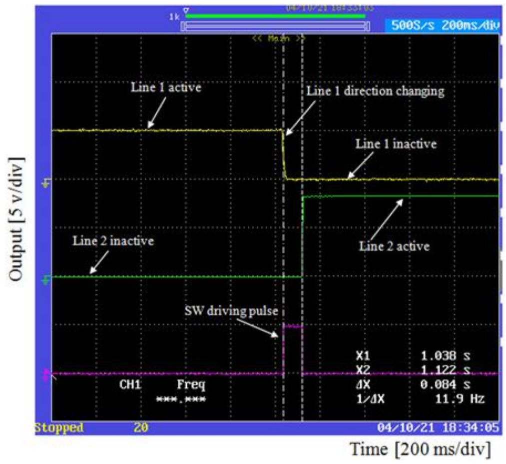


Figure 13. Switching speed at180 mA of fabricated PCF switch

Fig. 14 shows the relation of between switching speed and applied current. PCF fabricated optical switch is used for this experiment. In order to determine the relation between switching speed and current, we applied driving current from 80 mA to 200 mA. The switching speed is increase when the supplied current is increased. The maximum switching speed was 80 ms at 180 mA. The speed was constant when we applied more current.

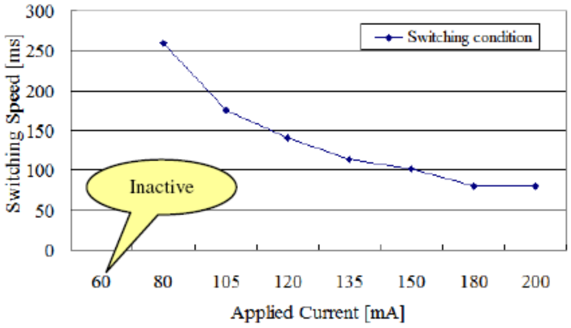


Figure 14. Relation between switching speed and applied current of PCF switch

V. CONCLUSION

In order to get a low insertion loss of the fabricated switch, we have considered many types of fiber processing method. Mechanical polishing method is superior to the other processes as mentioned. A polishing Jig was fabricated to polish fiber ends without using the permanent fixing method. Using these methods, an excellent fiber surface with stable reproducibility was gained in this study.

To fabricate the body and V-grooves of optical switch, a high-speed milling machine was used. We have assembled all the parts of optical switch successfully. An actuation test has done without any difficulty. 80 mA current was applied to the SMA coil. SMA coil was moved with movable fiber to the opposite side, and optical light was shifted properly.

ACKNOWLEDGMENT

A part of this work was performed at Venture Business Laboratory, Tohoku University, Japan. We would like to give special thanks to Prof. Masayoshi Esashi, and Prof. Yoichi Haga for giving us support technically.

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