Design and Characteristics of Large Displacement Optical Fiber Switch

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Design and Characteristics of Large Displacement Optical Fiber Switch

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***Abstract*— Plastic optical fiber (POF) is suitable for indoor local area network (LAN), for example, in-home or office networks, because of its flexibility and its ease of connection due to its relatively large core diameter. A 1 $\times$ 2 optical switch for indoor LAN using POF and a shape memory alloy (SMA) coil actuator with magnetic latches was successfully fabricated and tested. In this paper, the design concept and the characteristics of this switch are described. To achieve switching by the movement of a POF, large displacement is necessary because the core diameter is large (e.g., 0.486 mm). A SMA coil actuator is used for large displacement and a magnetic latching system is employed for fixing the position of the shifted POF. For this design, the insertion loss is 0.40 to 0.50 dB and crosstalk is more than -50 dB without index-matching oil. Switching speed is less than 0.5 s at a driving current of 80 mA. A cycling test was performed 1.4 million times at room temperature. Another optical fiber switch was fabricated and successfully actuated using plastic clad fiber (PCF). PCF also has a large core diameter (e.g., 0.20 mm) and optical switches using PCF will be useful for short distance networks between buildings.**

***Index Terms*—Indoor LAN, magnetic latch, optical switch, plastic optical fiber, shape memory alloy.**

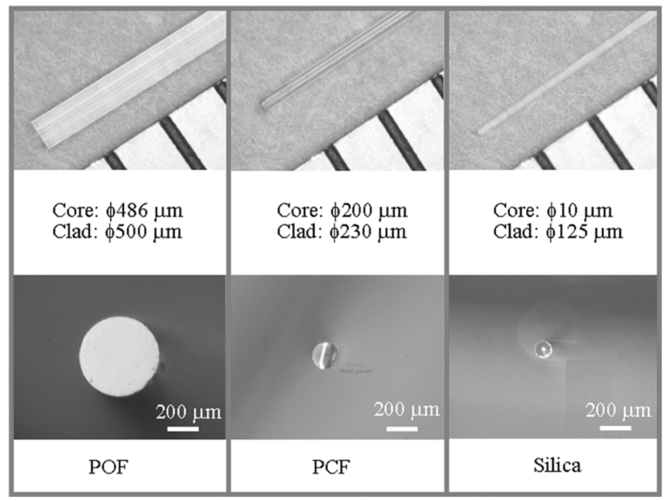

Fig. 1. Large diameter optical fiber (POF/ PCF) and conventional silica fiber.

I. Introduction

For many multimedia applications, such as television conferences, digital satellite broadcasting and digital television, a huge amount of video data is available both at home and in the office [1]. For 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. Small core silica optical fibers are widely used for communication systems. However, such small core (0.005 to 0.01 mm) optical fibers require high precision alignment between two fiber ends. As demand for applications of broadband systems for home or office LANs increases, it is predicted that information from the internet or broadcasting will be transmitted to information terminals, where it will be transmitted to the appropriate AV equipment using a POF network. Plastic clad fiber (PCF) also has a large core diameter (e.g., 0.20 mm), and an optical switch using PCF will be utilized for short distance networks between buildings. Fig. 1 shows an optical fiber (POF/PCF) with a large diameter, and a conventional silica fiber.

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The maximum data rate and propagation distance of SI POF (Eska MIU, Mitsubishi Rayon Co. Ltd.) are 500 MHz/50 m and 0.16 dB/m, respectively. On the other hand, those of GI POF (Eska GIGA, Mitsubishi Rayon Co. Ltd.) are 1 GHz/50 m and 0.17 dB/m, respectively, while those of H-PCF (HCS: OFS Fitel LLC) are 20 MHz/km and 6 dB/km, respectively.

In this paper, optical switches for optical fibers (POF and PCF) with large core diameter were developed. Optical switches of POF will be needed when indoor LAN becomes widely used in the near future. For example, 1 $\times$ 2 optical switches using POF will be useful in adding bifurcation to existing networks, such as in television conferences and monitoring of patients in hospitals. Another benefit of 1 $\times$ 2 optical switches is that the switch can be bifurcated without optical power loss resulting from the bifurcation.

For switching by movement of the POF, large displacement is required because the fiber has to be displaced a distance greater than its core diameter. A shape memory alloy (SMA) coil actuator is used because of its large displacement. SMA returns to its memorized shape when it is heated above a certain transition temperature. An SMA coil stretched from its memorized shape contracts when it is heated by application of an electrical current. An SMA coil actuator was used because its displacement is larger than an SMA wire actuator. In case of an optical fiber switch using an SMA wire, its displacement is a few micrometers, and thus silica fibers (core diameters of only 0.005–0.01 mm) were used [2]. In the present paper, the displacement of the fiber was 0.7 mm by using an SMA coil actuator.

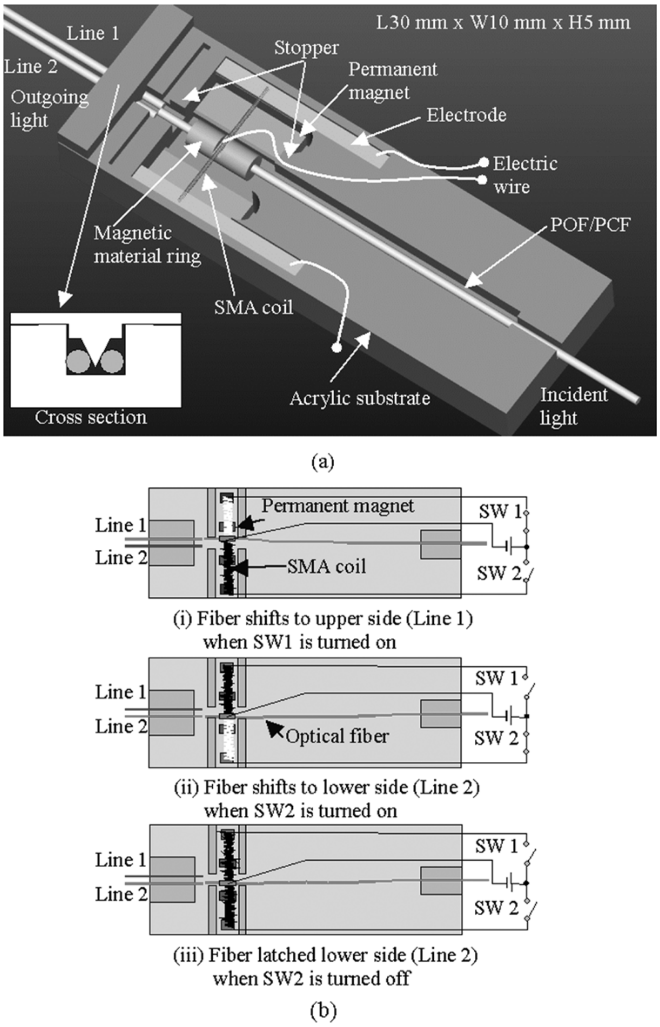

Fig. 2. (a) Structure of switch and (b) switching mechanism.

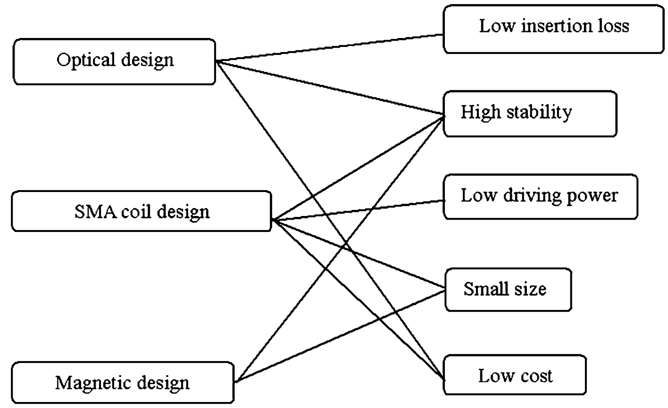

Fig. 3. Design concept of switch.

A magnetic latching system is used in this device for fixing the position of the shifted POF, and therefore a continuous current supply is not necessary. There are some optical fiber switches, which use solenoid coils and permanent magnets, which move and latch fiber magnetically [3], [4]. Such switches are for silica optical fiber and required displacement of the fiber is small.

II. Structure and Principle of Switch

The structure of the optical switch is shown in Fig. 2(a) and the switching mechanism is shown in Fig. 2(b). On the right side is a movable POF attached to the SMA coil and on the left are two fixed POFs. The fiber end on the left side and those on the right side face each other. The switch is operated by moving the POF. A large displacement of 0.5 mm is needed because the outer diameter of the POF is 0.5 mm. To achieve such a large displacement, an SMA coil actuator was used. If switch SW 1 in Fig. 2(b) is turned on, an electrical current flows through the upper half of the SMA coil, which is heated by Joule heat. When the upper half of the SMA is heated beyond a certain transition temperature, it contracts. A fiber, which is attached to the SMA, moves upward and light passes into the upper left side fiber (Line 1). If switch SW 2 in Fig. 2(b) is turned on, the same change occurs in the lower half of the SMA coil and the POF is moved to the lower side (Line 2). A magnetic ring is attached to the movable optical fiber and two permanent magnets are placed at both sides of the fiber. The permanent magnets attract and fix the location of the magnetic ring when the fiber moves to the upper or lower side. Because the magnetic latch fixes the position of the shifted POF, a continuous current supply is not necessary.

The SMA coil was stretched from memorized shape and shear strain was 4.3%. The acrylic substrate, which is the base for all the parts, was fabricated using a high-speed milling machine. The fibers on the left side were placed in the groove of the substrate and properly fixed by pressing them into a V-shaped extension as shown in the cross section of Fig. 2(a).

III. Design of the Optical Fiber Switch

A. Design Concept

Fig. 3 shows the design concept of the optical switch. Optimization of design parameters, material selection and manufacturing methods is achieved by utilizing information from the fields of optics, mechanics and electronics so as to realize low power consumption, compactness, light weight, high stability, and low cost. In the manufacture of the switch, to reduce the assembly time and to increase production, a simple process is used.

B. Switch Design

Fig. 2 shows the structure of the developed switch and Table I lists the switch parts.

C. Optical Design

An accurate assembly is required for low insertion loss and precise alignment of the POF. The main causes of insertion loss for optical switches are reflection of the POF end, lateral displacement, angular misalignment, the gap between optical fiber ends and roughness of the POF end. Reflection can be eliminated by using an index-matching oil, but packaging is complicated and the switching speed is decreased. The insertion losses were evaluated with and without index-matching oil. Minimum

TABLE I
PARTS OF 1 × 2 POF SWITCH

Items	Parameter
Fiber	Multi-mode POF (SI type), Core: 0.486, Clad: 0.50 mm
SMA coil	Ti -Ni, 0.2 (e.d.) mm × 0.05 (w.d.) mm × 4 (l.) mm
Permanent magnet	Neodium magnet, 6 (l) mm × 2 (w) mm × 1 (h) mm, flux density: 190 mT
Magnetic material ring	Fe, 1.5 (e.d.) mm × 0.5 (w.t.) mm × 4.0 (l.) mm
Ferrule	Polymer, ϕ 2.5 mm

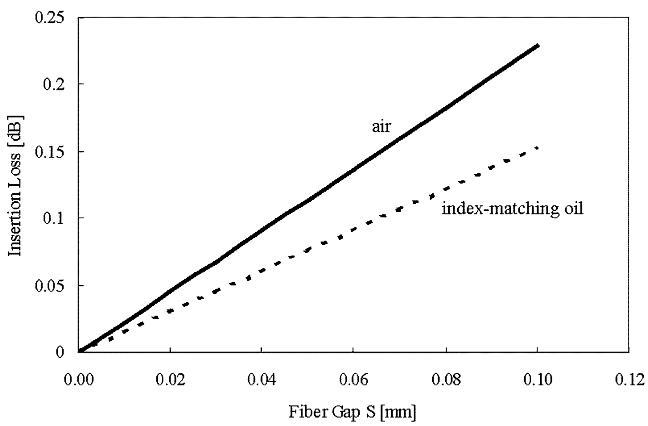

Fig. 4. Gap loss versus fiber end separation.

reflection loss without index-matching oil, L_1, is estimated by formula (1) (fiber index $n_1 = 1.49$, air index $n_2 = 1.0$).

$$L_1 = -10\log\left\{1-\left(\frac{n_1-n_2}{n_1+n_2}\right)^2\right\} \text{ dB}. \quad (1)$$

From this calculation, the reflection loss per fiber end is shown to be 4% (0.173 dB). As the optical signal passes through the switch with two fiber ends, the total reflection loss is 8% (0.346 dB).

Connection losses caused by the gap between the opposite fiber ends, L_2 (without index-matching oil) and L_2' (with index-matching oil), are estimated by (2) and (3), respectively, (fiber gap S; $NA = 0.5$; Core diameter $2a = 0.486$ mm; air index $n_2 = 1.0$; index-matching oil index $n_3 = 1.49$).

$$L_2 = -10\log\left(1-\frac{S\times NA}{4an_2}\right) \text{ dB} \quad (2)$$

$$L_2 = -10\log\left(1-\frac{S\times NA}{4an_3}\right) \text{ dB}. \quad (3)$$

If the gap becomes larger, the loss will increase. It is thus necessary to make the gap as narrow as possible (Fig. 4).

D. SMA Coil Design

A Ti-Ni SMA coil microactuator was used because the displacement of a coil-shaped SMA is larger than that of a wire-shaped SMA. An optical fiber switch using an SMA wire was fabricated, but its displacement was only a few micrometers because silica fibers (core diameters of only 0.005 to 0.010 mm) were used. In this study, displacement of the fiber was 0.70 mm by using an SMA coil actuator. A wire with a narrow diameter was used because of its relatively high electrical resistance. An SMA coil with the smallest wire diameter commercially available (0.05 mm) was selected. The external diameter of this SMA coil is 0.20 mm, its length is 4 mm and the number of turns is 9 per 1 mm.

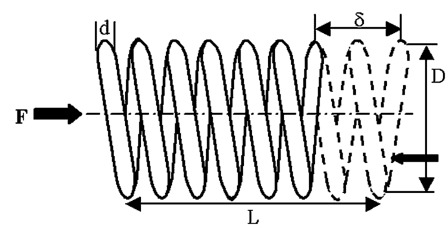

Fig. 5. Reduction of SMA coil actuator.

The switching force generated by the SMA coil increases as the length of the coil increases. The service life of the SMA coil becomes longer when the strain it is subjected to decreases. However, minimization of the coil length is required for a small package. The lifetime of the SMA coil increases when the shear strain (γ) it is subjected to decreases, where γ of the SMA coil is expressed as

$$\gamma = \frac{d\delta}{\pi n D^2}. \quad (4)$$

The generated force F of the SMA coil is expressed as

$$F = \frac{Gd^4\delta}{8nD^3} \quad (5)$$

where d is wire diameter (0.05 mm), D is coil diameter (0.15 mm), n is number of turns (36 turns), δ is displacement of the SMA coil (0.70 mm), G is modulus of rigidity (2.01×10^{10} N/m^2), γ is shear stress of wire and F is generated force as shown in Fig. 5. To increase the lifetime, the designed shear strain is 4.3% when the coil is extended to 4 from 2 mm. The length of the SMA coil was chosen to be 8 mm because most commercially available switches are 10 to 20 mm wide. Using formula (5), the generated force F of the SMA coil is 250 mN. The force of the magnetic latch must be lower than F for long service life actuation of the SMA coil.

E. Design of Magnetic Latch

Lateral and angular misalignment can be minimized by precise design and manufacturing. In the switch shown in Fig. 2, the lateral displacement and angular misalignment are caused by inadequate or excessive magnetic attraction force applied to the movable fiber. The optimal range for this force was determined. Fig. 6 shows the relation between the magnetic attraction force and the optical coupling condition. The physical

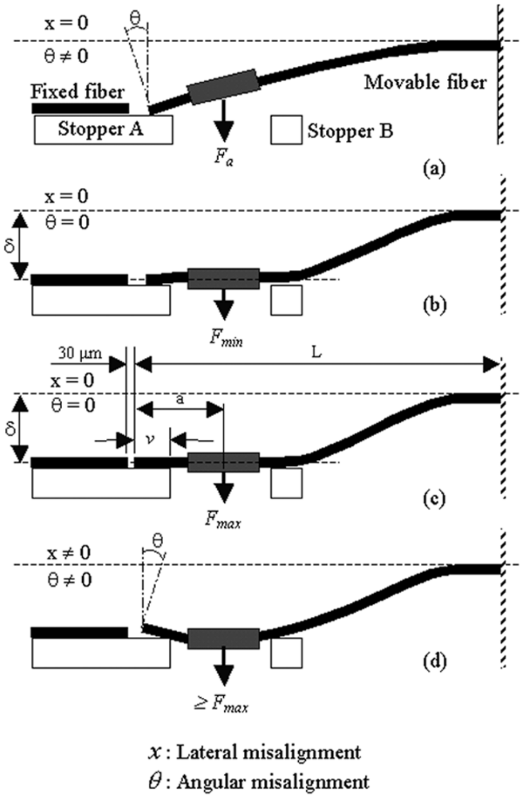

Fig. 6. Optical coupling condition for low loss of switch.

properties of the permanent magnets are given in Table I. External diameter, wall thickness, and length of the Ni magnetic material ring were 1.5, 0.5, and 4.0 mm, respectively. With a magnetic attraction force F_a, the end of the movable fiber is bent to stopper A, resulting in a small angular misalignment θ [Fig. 6(a)]. When F_a is too low, the movable POF is unstable when exposed to external vibration or impact. However, the deformation load is much stronger than F_a and the end of the movable fiber is bent upward at the edge of stopper A [Fig. 6(d)]. Therefore, the dimension and position of the permanent magnets should be chosen carefully so as to obtain the optimal magnetic attraction force, which will not cause lateral and angular misalignments. As shown in Fig. 6(b), when magnetic attraction force is stronger than $F_{\min}$, lateral displacement x and angular displacement θ will be 0. When the magnetic attraction force is weaker than $F_{\max}$ [Fig. 6(c)], the gap between the opposite fiber ends is minimized because the tip of the movable fiber slides to the opposite fiber end and v is the distance between the end of the movable fiber and the edge of stopper A. The deformation load of the optical fiber can be expressed as follows by treating the movable fiber as a nonstable beam with one fixed end and a supported end [5]

$$F_a = \frac{6EI\delta}{(L-a)^2(2L+a)} \quad (6)$$

$$F_{\min} = \frac{6EI\delta}{a(L-a)^2} \quad (7)$$

$$F_{\max} = \frac{6EI\delta}{(L-a)^2(a-v)} \quad (8)$$

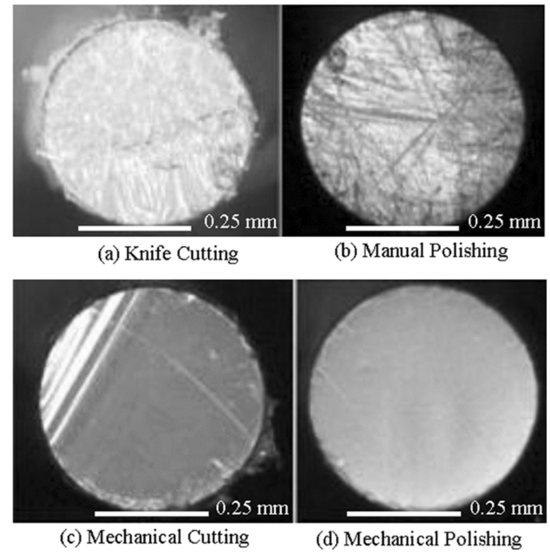

Fig. 7. Several processes of POF end.

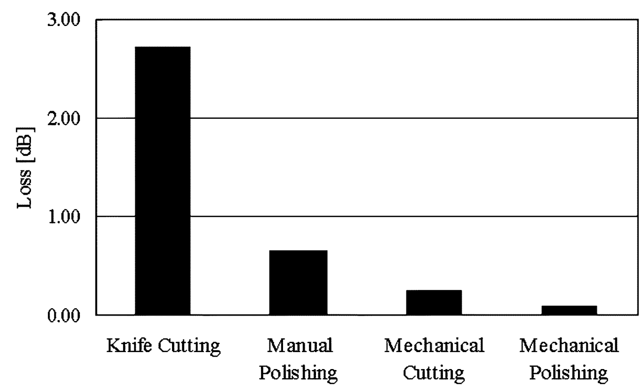

Fig. 8. Insertion losses of several techniques for processing POF ends.

where E and I are Young's modulus and the area moment of inertia of the movable fiber, respectively. In this calculation, $EI = 1.012 \times 10^{-5}\ \mathrm{Nm}^2$ is used and L and a are the length of the movable fiber and the application point of the force from the fiber end, respectively, (Fig. 6). δ is the bending distance of the movable fiber to the stationary fiber and the fiber tip moves a distance of 2δ during a switching operation.

$F_{\max}$ should be lower than 250 mN for SMA actuation and service life considerations as aforementioned in the discussion of SMA coil design. For the calculation of L, the following values were used: $a = 4.5$ mm and $v = 0.5$ mm. For a long lifetime of SMA, $F_{\max}$ was set at 40 mN. By using (8), calculated L was 24 mm.

IV. Fabrication

A. Processing of POF End

A smooth POF end is necessary for minimization of insertion loss. Comparison of various processes of POF ends with measured insertion losses are shown in Figs. 7 and 8, respectively.

Mechanical polishing is superior to other techniques such as knife cutting, manual polishing and mechanical cutting for attaining a smooth surface with minimal insertion loss. For this

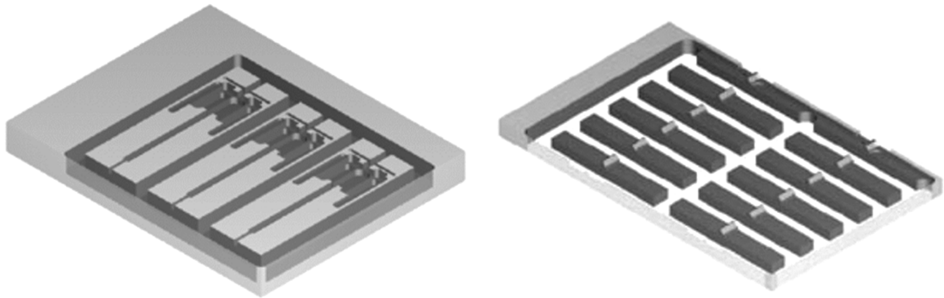

Fig. 9. Design of acrylic substrate and V-shaped outward extension.

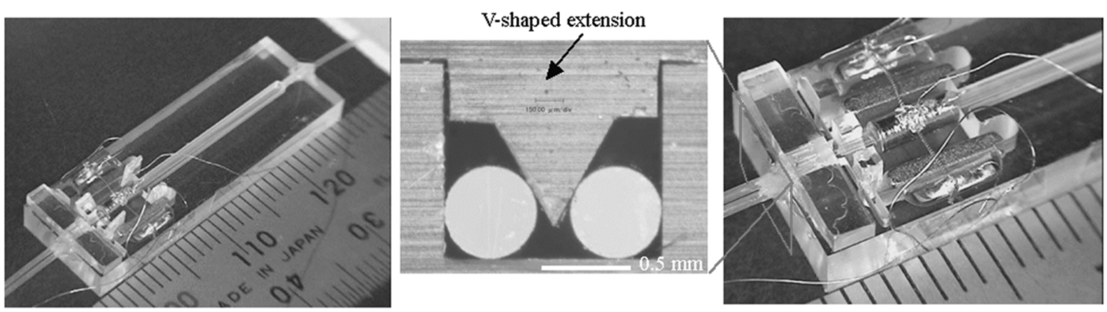

Fig. 10. Fabricated optical switch (a) structure of POF switch; (b) cross section of left side switch; (c) enlarged view of left side of POF switch.

reason, a mechanical polishing technique was used for the POF switch.

B. Design and Fabrication of Substrate

A high-speed milling machine was used for cutting the acrylic substrate. Before the processing, appropriate tools and processing conditions were chosen and checked using a simulator [Fig. 9(a)].

The acrylic substrate was cooled by water to avoid deformation during high-speed milling. A V-shaped extension for alignment of optical fibers, as shown in Fig. 9(b), was fabricated using the same milling machine. Many acrylic structures and V-shaped caps were batch fabricated from the acrylic plate.

C. Assembly Process

The fabricated POF switch is shown in Fig. 10. The aforementioned parts were assembled on the processed acrylic substrate as follows:

1) Cu electrodes for driving of the SMA were attached to the substrate with adhesive.
2) The middle of the SMA coil was fixed to a ring made of magnetic material and connected to the electric wires.
3) Two permanent magnets were fixed to each predetermined position of the substrate.
4) The movable side of the POF was inserted into the magnetic ring and fixed using adhesive.
5) Two fibers were placed in the grove of the substrate and properly fixed by pressing from upper side using a V-shaped outward extension as shown in Fig. 10(b).
6) The gap between the opposed POF ends was adjusted under a microscope.

TABLE II
CHARACTERISTICS OF 1×2 POF SWITCH

Parameter	Results of POF switch
Holding current	0
Insertion loss	0.40 – 0.50 dB (without index-matching oil) 0.06 – 0.09 dB (using index-matching oil)
Cross talk	≤ – 0.50 dB (without index-matching oil) ≤ – 0.58 dB (using index-matching oil)
Latching force	40 mN
Generated force of SMA coil	250 mN
Switching time	500 ms
Durability	> 1,400,000 cycles of switching
Actuation voltage	0.7 V
Actuation current	80 mA
Dimensions	30 mm (L) × 10 mm (W) × 5 mm (H)

V. RESULTS

A. Performance Evaluation of POF Switch

Size and specifications of the fabricated POF switch are shown in Table II.

B. Evaluation of Coupling Loss

A 650-nm laser diode was used as a light source. The intensity of the light emitted by the output fibers was measured as shown in Fig. 11. In this measurement, index-matching oil was not used. To measure coupling loss, the intensity of output light from the switch [Fig. 11(ii), (iii)] was compared with that of the reference POF [Fig. 11(i)]. All of the pass lengths were 300 mm. The fiber gap, lateral displacement, and angular misalignment were 0.030 mm, 0 mm, and 0 deg, respectively. The insertion loss was 0.50 dB or less, namely, a minimum value of 0.40 dB

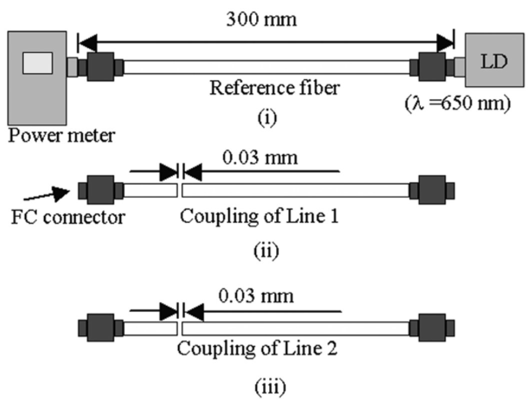

Fig. 11. Measurement setup for coupling loss evaluation.

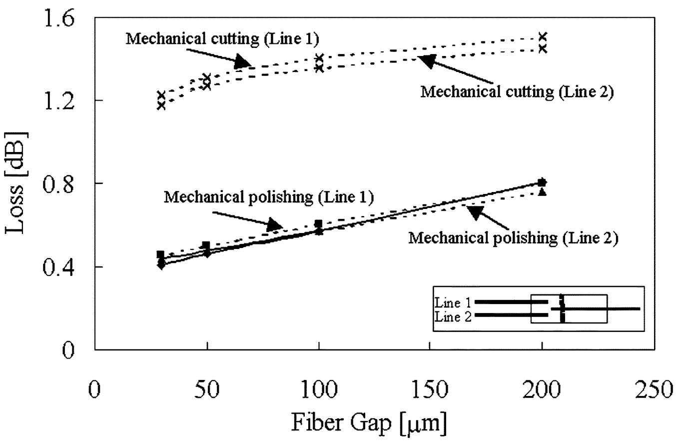

Fig. 12. Comparison between calculated and measured coupling loss (Calculated: dashed line; measured: solid line).

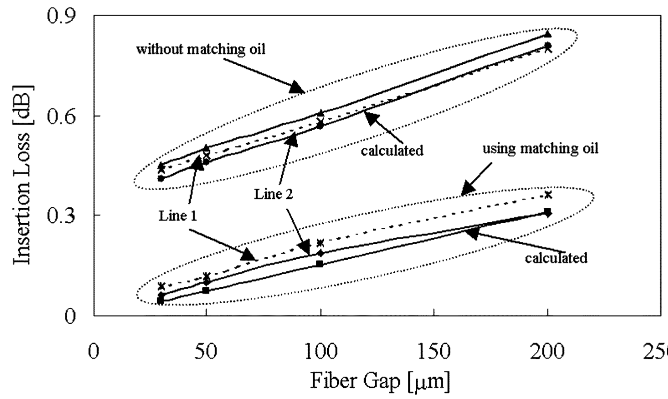

Fig. 13. Comparison between coupling loss when index-matching oil was used and was not used.

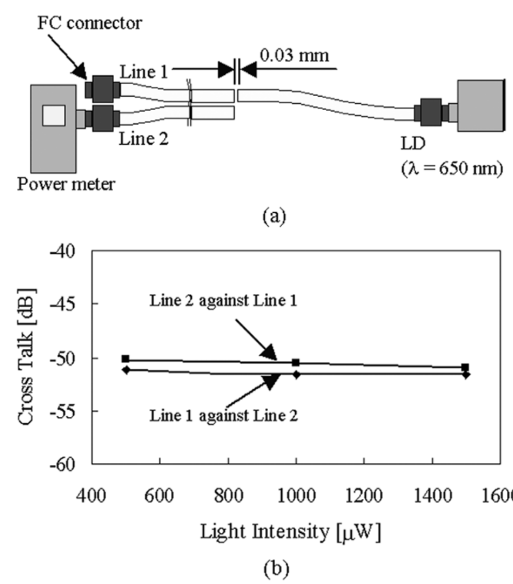

Fig. 14. Crosstalk measurement method and results. (a) Crosstalk measurement setup. (b) Measured crosstalk.

to a maximum value of 0.50 dB when mechanical polishing of the POF ends was performed. As shown in Fig. 12, calculated insertion loss versus fiber gap using (1) and (2) mentioned in Section III and measured insertion loss versus fiber gap were almost same. Insertion loss of conventional optical switches for communication is almost always less than 1 dB [3], [6], [7].

Comparison between coupling loss using index-matching oil and coupling loss without index-matching oil is shown in Fig. 13. In this case, mechanically polished ends were used. The insertion loss of the fabricated switch was 0.50 dB or less, namely, a minimum value of 0.40 dB to a maximum value of 0.50 dB when index-matching oil was not used. When index-matching oil was used, insertion loss was less than 0.10 dB, namely, a minimum value of 0.06 dB to a maximum value of 0.09 dB.

The insertion loss due to temperature change was evaluated. The maximum operation temperature of the POF employed in this switch is 70 °C, and change of measured coupling loss was less than 0.07 dB when the condition was changed to 23 °C–70 °C.

To evaluate the influence of temperature of the POF due to heating of the SMA, temperature change of the magnetic material ring was measured with a thermocouple. The temperature rose from 28 °C to 31 °C when the SMA was actuated.

The setup to measure crosstalk and the results are shown in Fig. 14(a) and (b), respectively. Cross talk was more than −50 dB when index-matching oil was not used.

POF/PCF switches are easily connected to each other because of their large core diameter and large NA. Thus, the insertion and reflection losses are not considered to be significant over the short distances that the signal travels. In the future, the reflection loss will be evaluated theoretically and experimentally.

C. Continuous Switching and Latch Confirmation Test

A continuous switching test was performed at room temperature, and after 26 000 cycles of switching, the SMA coil failed. The switching and measurement system is shown in Fig. 15. Latching power was 100 mN and driving current was 80 mA. By decreasing latching power to 40 mN, 1.4 million cycles of switching were realized at room temperature. Switching speed was 0.5 s at a driving current of 80 mA. The insertion loss was 0.5 dB for 1.4 million cycles of switching as shown in Fig. 15(c). The SMA coil actuator has a simple structure and is suitable to satisfy these demands. When the latching force was decreased to less than 20 mN, the magnetic latch was unable to hold the

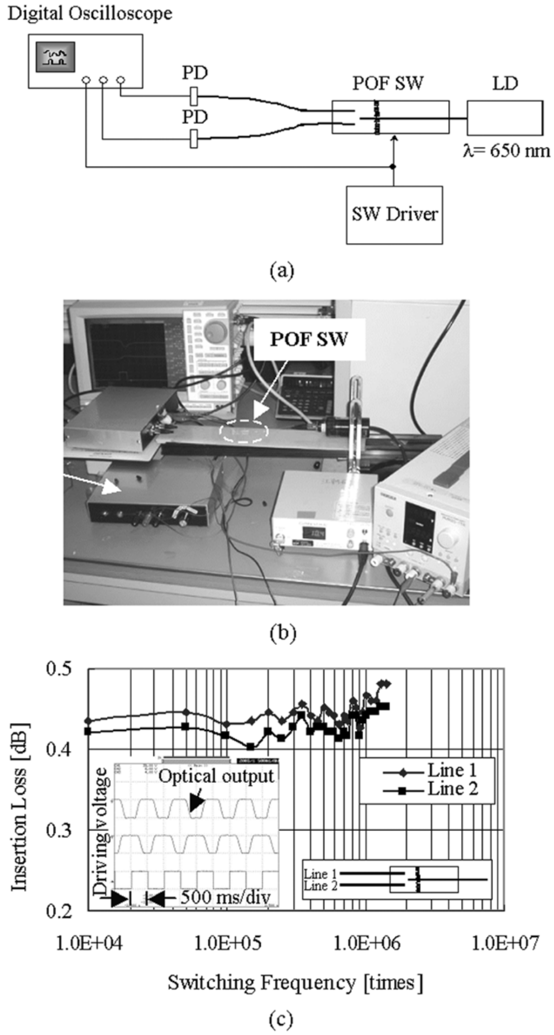

Fig. 15. Switching and measurement system (a) continuous switching system. (b) Photograph of measurement system. (c) Insertion loss change under continuous switching.

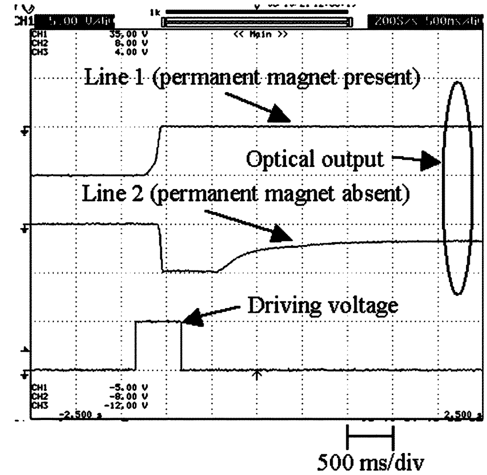

Fig. 16. Latch confirmation test.

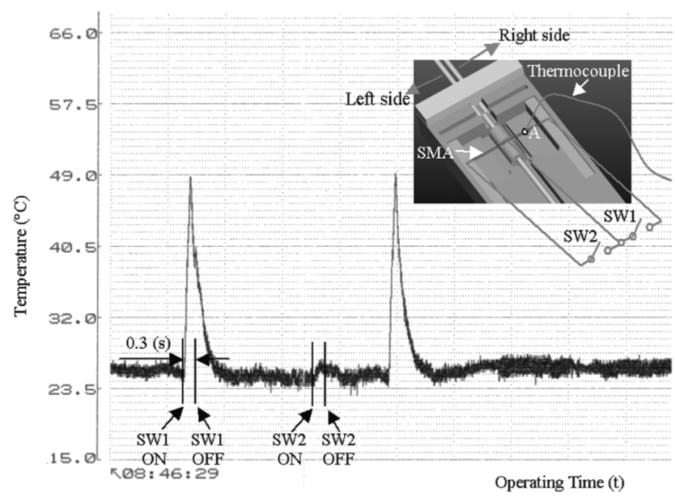

Fig. 17. Measured temperature of SMA coil.

shifted POF properly after driving current was turned off. When the magnetic latching power was insufficient, the shifted fiber gradually returned to the opposite side and insertion loss increased as shown by Line 2 in Fig. 16. Appropriate magnetic latching force is essential for this switch.

After six months in a holding position on the right side, the device was switched to the left side. Measured latching force 40 mN was not changed. No problems with fixing or releasing were observed after latching for a long period.

D. Measured Temperature of SMA Coil

The temperature of the right side of the coil was measured at location A (Fig. 17) with a thermocouple. When SW1 was turned on, the temperature of the right side of the SMA coil rose to over 50 °C, while the temperature of the right side of the SMA coil slightly rose to 25 °C when SW2 was turned on. Therefore, the thermal isolation between the right side and left side of the SMA is considered to be sufficient.

Though the measured temperature of the actuated half of the SMA is around 50 °C, malfunction in a high temperature environment (over 50 °C) is avoided because both sides of the SMA are heated simultaneously.

Plastic clad fiber (PCF) with other large external diameters (e.g., 0.5 mm) can be used in this device. An optical switch (1 × 2) with the same dimensions of 30 mm (L) × 10 mm (W) × 5 mm (H) and using PCF and an SMA coil actuator with a magnetic latching system was fabricated and successfully actuated.

VI. Conclusion

A 1 × 2 optical switch for indoor LAN using POF was developed and its switching was successfully confirmed. To realize large displacement of POF, an SMA coil microactuator was utilized. A magnetic latch system was used for fixing the position of the displaced POF. A short description of the developed optical fiber switch is given below.

1) A 1 × 2 optical switch using POF and an SMA coil actuator with a magnetic latch was successfully fabricated and actuated. The dimensions of the switch were 30 mm (L) × 10 mm (W) × 5 mm (H).
2) Mechanical polishing of the POF end can achieve a smooth surface for the optical switch.

3) The insertion loss of the fabricated switch was 0.50 dB or less, namely, a minimum value of 0.40 dB to a maximum value of 0.50 dB, when index-matching oil was not used. When index-matching oil was used, insertion loss was less than 0.10 dB, namely, a minimum value of 0.06 dB to a maximum value of 0.09 dB.
4) Continuous switching operation was confirmed and switching speed was less than 0.5 second at a driving current of 80 mA. This speed is sufficient for indoor LAN.
5) A continuous switching test was performed and 1.4 million cycles of switching were realized at room temperature.
6) Crosstalk was more than −50 dB without index-matching oil.
7) An optical fiber switch using PCF instead of POF was fabricated and successfully actuated.

The developed switches are the first optical switches to be realized which use an optical fiber having a large diameter (0.5 mm). To fabricate the substrate at low cost, injection molding instead of high-speed milling machining can be applied. The amount of SMA coil used per switch is small and the cost is relatively low. In the future, practical experiments in the field of indoor LAN using this fabricated optical switch will be conducted.

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