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Fabrication and Characteristics of Plastic Optical Fiber Directional Couplers

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Directional couplers of gradient-index plastic optical fibers were fabricated and characterized. In particular, we have employed a core-facet technique to make the directional couplers, which require mechanical side polishing and linkage. We have measured insertion loss, excess loss, and coupling ratio of the fabricated couplers as a function of polishing depth and coupling length. We found that polishing depth of ~300 μm and coupling length of ~35 mm are optimum conditions for minimizing the insertion and excess losses and for achieving 1:1 coupling ratio.

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I. INTRODUCTION

Due to rapidly increasing demand of telecommunications, many countries are developing advanced optical communication infrastructures, which will deliver fiber optic cables directly to homes, known as the Fiber-to-the-Home (FTTH) project. Since conventional optical glass fibers are brittle and hard to connect, it would be very difficult to install glass fibers in small office, home, and mobile environments directly. If we use plastic materials for making optical fibers, we may easily solve these problems associated with optical glass fibers [1]. Therefore, several universities and research centers in Japan and U.S.A. have been working on plastic optical fibers (POFs) and some companies have already started selling POFs for local area network (LAN) applications [1-6].

Especially, graded-index POFs (GI-POFs) have been extensively investigated, since they can be strong candidates for a high bandwidth medium for relatively short-distance data transmission. In 1988, Koike et al. in Keio university produced high-quality and cost-effective GI-POFs based on polymethyl methacrylate (PMMA) materials by utilizing an interfacial gel polymerization method [7],[8]. In addition, it has been demonstrated that high transmission bandwidth can be achieved by using the PMMA GI-POFs [9]. After then, the overall system, including light sources, for high bandwidth data transmission with POFs has been developed in the field of industrial automation and automotive applications. However, there are few reports on the GI-POF devices like splitters, attenuators, couplers, etc.

In this paper, we present fabrication and characterization of directional couplers of the GI-POF. A core-facet technique, which requires mechanical side polishing and UV adhesive material link, was employed to fabricate GI-POF directional couplers. Insertion loss, excess loss, and coupling ratio of the fabricated directional couplers were measured for different polishing depths and coupling lengths systematically. The experimental results showed that optimum polishing depth and coupling length can be achieved for the multi-mode GI-POF directional couplers.

II. FABRICATION OF GI-POF OPTICAL DIRECTIONAL COUPLERS

Optical directional couplers (ODCs) are essential elements for the construction of optical networks, LANs for short distance applications, and industrial automation. Various types of ODCs have been proposed and developed such as butt couplers, core-fusion couplers, bend couplers, and core-facet couplers. A butt-coupler is quite simple to make but has high excess loss. The advantage of a core-fusion coupler is ease of alignment and fabrication of $N \times N$ configurations. However, it requires relatively expensive equipment. A bend coupler is also easy to fabricate but has dependence on mode dispersion and limited coupling ratio. A core-facet ODC, fabricated in our research, has advantages of precise control of coupling region and reproducibility, even though rather complicated grinding, polishing, and alignment are needed [10].

Fig. 1 shows a schematic diagram of our GI-POF ODC fabricated by using a core-facet fabrication technique. As can be seen in Fig. 1, optical losses and connection ratio can be accurately controlled by adjusting polishing depth and coupling length of the GI-POF. Note that coupling length is dependent upon the bending radius. In our experiment, bending radii of 150 *mm*, 300 *mm*, 450 *mm*, and 600 *mm*, corresponding to the coupling lengths of 19 *mm*, 27 *mm*, 33 *mm*, and 37 *mm*, respectively, were utilized.

In order to fabricate GI-POF, PMMA GI preform was prepared by diffusion of polymer into a liquid monomer phase. At first, a cylindrical glass tube reactor was filled with the mixture of monomer (liquid phase), initiator, and chain transfer agent with a lower refractive index and density. Then, a co-polymer rod (solid phase) with a higher refractive index and density was replaced in the center of the reactor. The central solid rod and tube reactor were designed to be rotated independently. The tube reactor and the central solid rod were rotated as fast as 1000 rpm. However, rotation speeds of the tube reactor and the solid rod were slightly different up to 6-60 rpm. In stage I, they were rotated at room temperature in order to obtain a graded concentration profile with radial direction by diffusion and centrifugal force. The rotating speed difference between a rod and a tube reactor, which generates Couette flow between a rod surface and a tube reactor wall, results in a laminar shear mixing (LSM) in the liquid phase [11]. The LSM greatly reduced the concentration fluctuation in the tangential direction. Therefore, the overall graded index profile can be controlled by the diffusion time and the rotating speed. The reactor and rod were rotated for a couple of hours to obtain a smooth concentration profile, and then temperature was elevated to fix a generated profile. From the fabricated PMMA GI preform, POFs of GI profile were fabricated by a heat-drawing technique [12]. The refractive indices of middle and edge of GI-POF were 1.513 and 1.491, respectively. Numerical aperture (N. A.) and diameter of GI-POF were 0.25 and 750 μm, respectively.

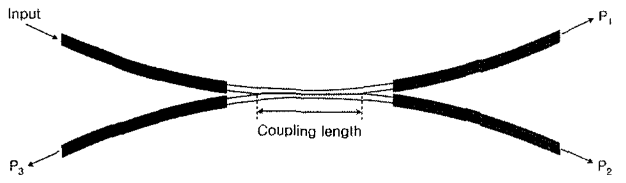
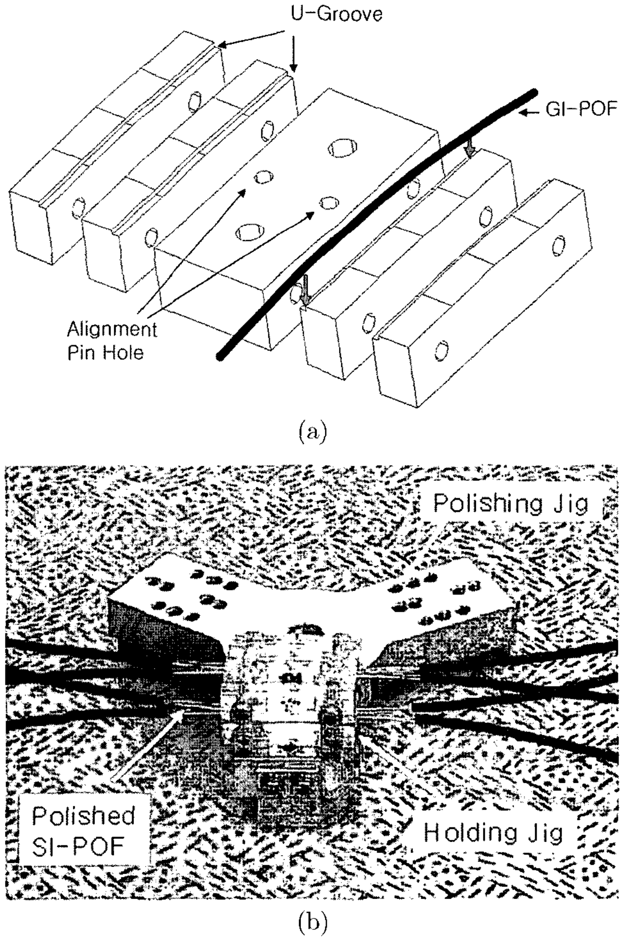


FIG. 1. Schematic diagram of GI-POF directional optical coupler.

Fig. 2 shows a GI-POF mounted on specially designed JIGs for side-polishing. Two identically side-polished GI-POF were precisely positioned together to form a ODC, as schematically shown in Fig. 1. A UV adhesive material with refractive index of 1.49 was used for bonding two fibers and UV light source of P=9850 mW/cm^2 was exposed for ~10 minutes. More than 20 GI-POF ODCs for each bending radius of 150 *mm*, 300 *mm*, 450 *mm*, and 600 *mm*, were systematically fabricated.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 3 shows our experimental setup for measuring insertion loss, excess loss, and coupling ratio. Since launching condition is very important, a lens of N. A.=0.25 was utilized. To characterize the optical transmission of the ODC based on plastic optical fiber, a semiconductor laser diode (TOLD9462MC/MD, Toshiba) of 5 mW operating at 650 nm was utilized. The input power and the output power at the ports 3 and 4 were carefully measured by a CW power meter (Coherent Field-master).



(a)

(b)

FIG. 2. Specially designed JIGs for side-polishing of POF.

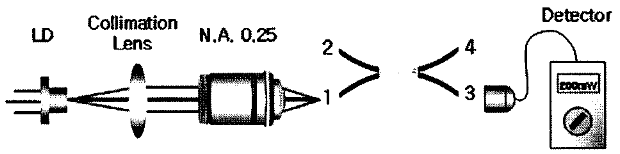


FIG. 3. Experimental setup for measuring insertion loss, excess loss, and coupling ratio.

The insertion loss in *dB* is defined by

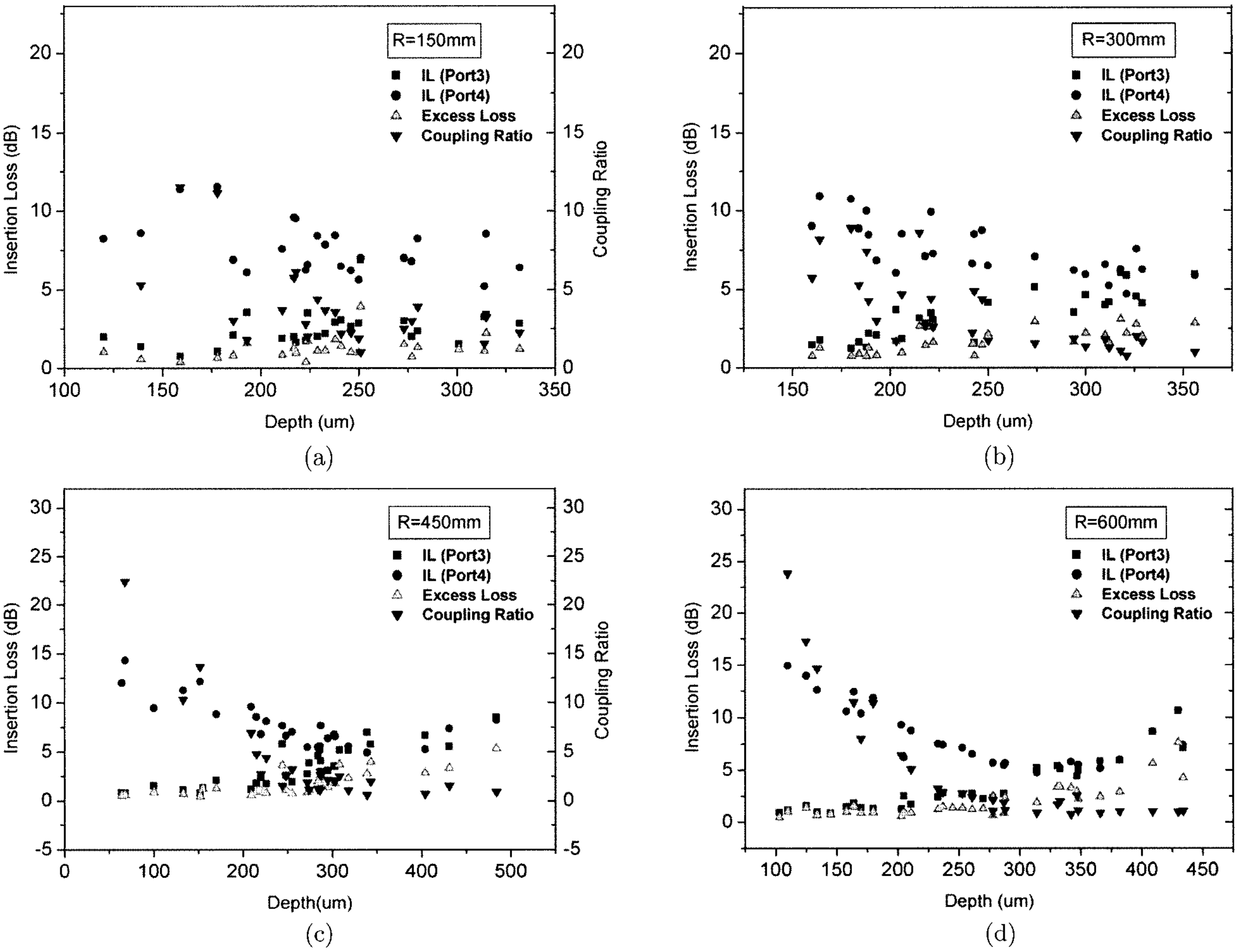
$$Insertion\ Loss\ (IL)\ =\ -10\log\frac{P_{output3}}{P_{input1}}\ \text{or}\ -10\log\frac{P_{output4}}{P_{input1}} \qquad (1)$$

where $P_{output1}$, $P_{output3}$, and $P_{output4}$ are the input power, the output power at the port 3, and output power at the port 4, respectively [1-3]. The coupling ratio is defined by

$$Coupling\ Ratio\ (CR)\ =\ \frac{P_{output4}}{P_{output3}} \qquad (2)$$

Fig. 4 (a), 4 (b), 4 (c), and 4 (d) show the measured data of insertion losses, excess loss, and coupling ratio as a function of polishing depth for the bending radii of 150 *mm*, 300 *mm*, 450 *mm*, and 600 *mm*, corresponding to the coupling lengths of 19 *mm*, 27 *mm*, 33 *mm*, and 38 *mm*, respectively. Fig. 4 (a) and 4 (b) show that the insertion loss at the port 3 is increased as the polishing depth is increased. In contrast, the insertion loss at the port 4 is decreased with increasing the polishing depth, as can be expected. Similar characteristics can be found in Fig. 4 (c) that the insertion loss at the port 4 is decreased with increasing the polishing depth up to ~300 μm.

However, unexpectedly, Fig. 4 (c) reveals that the insertion loss at the port 4 for 450 *mm* bending radius is slightly increased for the polishing depths of ≥300 μm, even if the insertion loss at the port 3 continues to increase as observed above. This increasing behavior of the insertion loss at the port 4 for the polishing depth of ≥300 μm is even more clearly observed in Fig. 4 (d). It is attributed to competition between proximity due to polishing depth and the coupling length.



(a) (b)

(c) (d)

FIG. 4. Insertion losses, excess loss, and coupling ratio versus polishing depth for (a) R = 150 mm, (b) R = 300 mm, (c) R = 450 mm, and (d) R = 600 mm

In addition, for the polishing depth of at around 300 μm and bending radius of 450 *mm* and 600 *mm*, corresponding the coupling length of 33 *mm* and 38 *mm*, the insertion losses at the port 3 and the port 4 are quite similar, resulting in the coupling ratio of 1 :1. The excess loss is also maintained to be below 3 *dB* for up to 300 μm polishing depth, although it is dramatically increased with increasing the polishing depth of ≥300 μm.

Therefore, it can be concluded that the polishing depth of ~300 μm and coupling length of ~35 *mm* are optimum conditions to minimize the insertion losses while keeping low excess loss and achieving a 1:1 coupling ratio. Our experimental results indicate the feasibility of finding the optimum polishing depth and coupling lengths of various GI-POFs of large diameter, for which analytical and/or computational simulations can not be easily applied to find the optimum condition.

IV. CONCLUSIONS

We have fabricated the symmetric GI-POF ODCs by using a core-facet technique. The insertion loss, excess loss, and coupling ratio of the fabricated GI-POF ODCs were investigated for various polishing depths and coupling lengths. It is found that polishing depth of ~300 μm and the coupling length of ~35 *mm* are optimum conditions to minimize the insertion losses, maintain the excess loss less than 3 *dB*, and achieve 1:1 coupling ratio. We believe that our experimental results can be utilized for fabricating optimum ODCs based on the GI-POFs with large core diameters.

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