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1×2 Y-BRANCH PLASTIC OPTICAL FIBER WAVEGUIDE COUPLER FOR OPTICAL ACCESS-CARD SYSTEM

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Abstract—Design and fabrication of optical code generating devices based on plastic optical fiber (POF) for security access-card system is presented. The POF waveguide coupler will utilize two basic designs: 1×2 Y-branch coupler as the main device structure and 1×2 asymmetric coupler which allows non-symmetric optical power splitting. The Y-branch coupler are based on two designs: A metal-based POF coupler with a hollow taper waveguide and an acrylic-based POF coupler with optical glue for the taper waveguide region. The Y-branch device is composed of input POF fiber, middle taper waveguide and output POF fibers. Simulation based on non-sequential ray tracings have been performed on both types of POF couplers. Low cost aluminum and acrylic based materials are used for the substrates. Fabrications of the POF couplers are done by producing the device mold insert using CNC machining tool and POF fibers are then slotted into the Y-branch coupler mold insert. The insertion loss for both devices are about 8 dB.

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1. INTRODUCTION

Plastic Optical Fiber (POF) is a well known medium for short range data communication due to its large-core size, multimode properties, low cost and robust characteristics. In addition, POF is also being used in optical signaling, lighting and also decoration system. Other specialty applications of POF are in the automotive, entertainment, and sensor industries [1]. In all of these applications, it is necessary to split or combine the optical signals using passive components. In the silica fiber industry, passive optical devices are well known and have been produced. However, in POF technology, many such devices are still under development [1]. Waveguide-based POF devices research are limited due to the fact that highly multimode devices have a smaller market especially for data communication application due to the high attenuation of POF compare to that of glass optical fiber [1]. The attenuation of POF at 520 nm wavelength is 100 dB/km whereas for a single mode glass fiber the attenuation is only 0.2 dB/km at 1550 nm [2].

Optical sensing is a broad field encompassing many applications. One of the possible application in optical sensor is optical code generation for security access application. The application of optical components in physical security systems have been known but none uses the concept of applying a unique series of output power from a waveguide coupler device for code generation.

An optical code generating device which is implemented in an optical access-card system is designed and fabricated using POF waveguide couplers. By a simple arrangement of the output power of the waveguide coupler, a unique code can be generated for access-card system application. The output powers from the waveguide coupler are arranged in series which represent a unique code. This code generating device can be embedded to a portable unit without the need of any active components such as battery or laser diode. The active components are located in the receiver section. Another feature of the waveguide coupler is that it has a large core size which allows more flexibility in waveguide coupling to a light source and detectors. The optical code generating device will be based on POF coupler. The code generating device will start off with a simple 1×4 coupler structure. Higher level devices can be constructed using simple cascading technique. The basic structure for all code generating devices will be the 1×2 Y-branch coupler. The 1×2 Y-branch coupler will be cascaded with another type of coupler which is the 1×2 asymmetric coupler. The design of the asymmetric coupler has been reported and published [3, 4]. In this paper, we will illustrate the development on the design and fabrication of the 1×2 Y-branch POF coupler only.

We have designed and fabricated two types of 1×2 POF coupler: (i) Metal-based coupler with hollow taper waveguide region and (ii) acrylic-based coupler with an optical glue taper waveguide region. Non-sequential ray tracing has been performed on both device structures. Fabrication of the devices have been done using CNC machining technique.

2. SYSTEM OVERVIEW

The optical access-card system is a system with a portable optical code generating component and a reader for code verification. The heart of the access-card system will be the waveguide coupler device. The waveguide coupler can have N-number of output ports and one input port. An asymmetrical waveguide design is used to design the device which allows the input power to split into any value from 0% to 100%. In addition, due to its unidirectional functionality, the design of the waveguide is less rigid compare to a bidirectional waveguide design.

Figure 1 is a block diagram showing how the output power of the waveguide coupler are utilized for generating a unique optical code for the security access system. In this figure, a 1×4 waveguide coupler is illustrated. The characters A, B, C and D represent generic terms for the codes. Referring to this figure, by a simple arrangement of the output power, a series of optical codes can be produced. Two examples of optical codes generated are shown in this figure (Code 1 and Code 2). Each output port provides a distinctive power value which is achieved by a unique design of the waveguide coupler. The value for the output power can be easily controlled by using the asymmetrical coupler design. In this example, the two codes are the number 12 : 50 : 20 : 10 (Code 1) and 35 : 15 : 6 : 22 (Code 2).

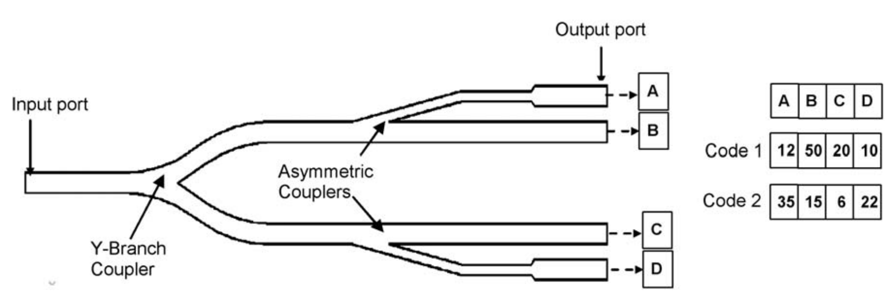


Figure 1. Code generating component for a 1×4 waveguide coupler device (4-digit code).

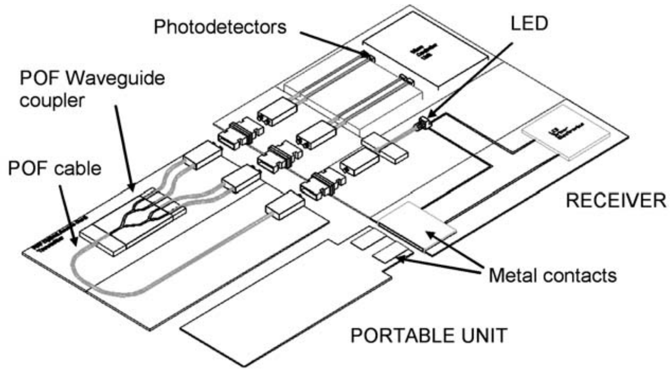


Figure 2. CAD diagram of the proposed optical access-card system.

Figure 2 is the CAD diagram of the optical access-card system utilizing the POF waveguide coupler. The waveguide coupler is embedded in a portable unit which can be slotted into an appropriate receiver/card reader section. A light source (LED) will be positioned at the receiver section. The coupling of the light source and the waveguide coupler can be done using a short 1 mm core size POF fiber (as part of the portable unit).

A general expression of the number of code combination can be obtained using combinatory number theory. The solution to the number of possible codes that can be generated, K_N is obtained as follows:

$$K_N = \binom{M_{\max} + N}{N} \tag{1}$$

where N is the number of output ports of the waveguide coupler and $M_{\max}$ is the maximum output power ratio of the waveguide which is taken as 100 [5].

3. DEVICE DESIGN

The 1×2 coupler is the simplest coupler design where the input optical power is split into two. The basic coupler design will utilize a simple 1×2 Y-branch coupler. In addition to the simple 1×2 Y-branch coupler, several 1×2 asymmetric couplers with different splitting ratios have been designed [3, 4].

The Y-branch coupler is also chosen because it can be easily connected to 1×2 asymmetric couplers by simple cascading technique. This final device structure can be used as the 4-digit code optical code generating device. Higher level waveguide ($1 \times N$) can be easily

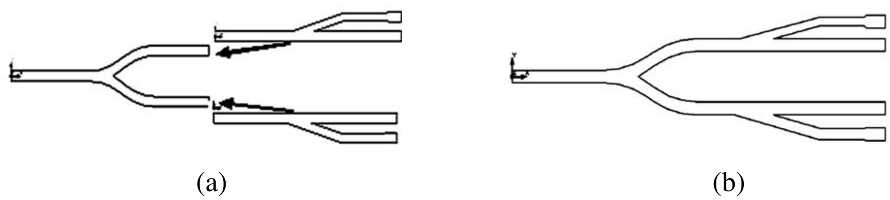


Figure 3. (a) 1×2 Y-junction coupler before joining with two asymmetric 1×2 couplers (b) 1×4 coupler with asymmetric branches.

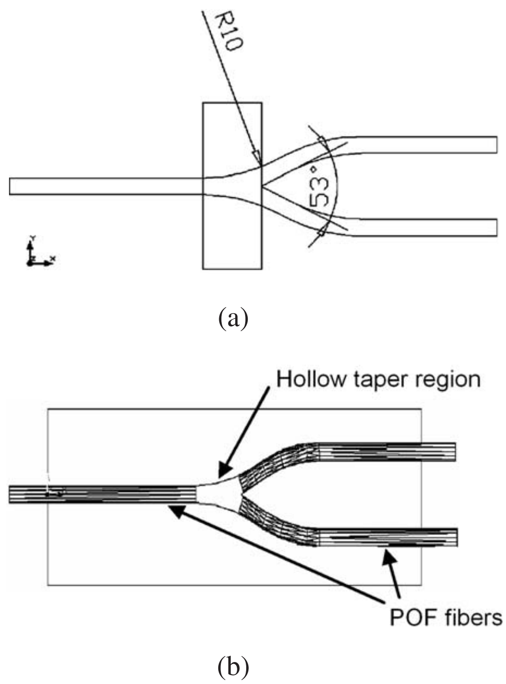


Figure 4. Metal-based 1×2 POF coupler (a) 2D CAD layout (b) POF coupler layout with input and output POF fibers.

constructed using these basic waveguide components. The cascading of the Y-branch coupler with the asymmetric couplers is shown in Figure 3.

The first design will be the metal-based 1×2 POF Y-branch coupler with a hollow taper waveguide shown in Figure 4. In this coupler design, the splitting angle is set large at an angle of 53° as shown in Figure 4(a). Figure 4(b) shows the POF coupler block with the input and output POF fibers inserted and the hollow taper region in the middle. The 1×2 POF coupler has been designed using a simple metallic mold insert. The POF coupler device is composed of three sections: An input POF waveguide, an intermediate hollow taper waveguide and output POF waveguides. The waveguide taper region is constructed using hollow structure which allows waveguiding to occur by simple reflection on the metallic inner surface. The input and output waveguides are constructed using POF fibers which are slotted into a Y-shaped mold insert, shown in Figure 4(b). The POF fibers are slotted until the fibers are positioned just before the waveguide taper region. The width of the grooves has been set at 1 mm which allow a 1 mm core POF fiber to fit in firmly.

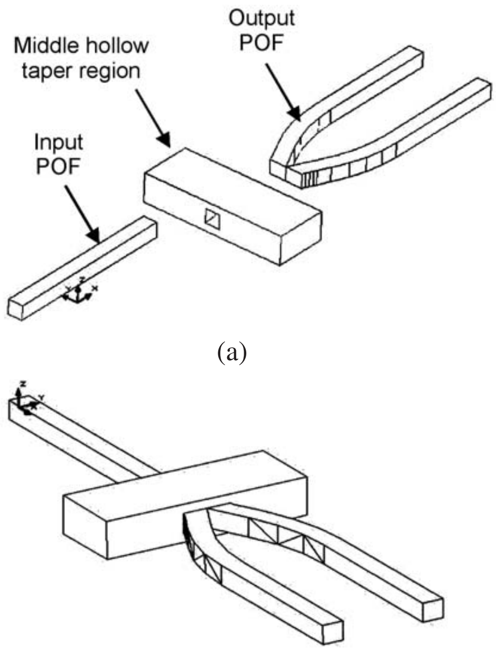
A metallic hollow-type structure has been proposed because of the device large core size (1 mm) and the ease of producing the mold insert. Light propagates along the waveguide solely by reflection on the metallic inner-surface. The hollow waveguide structure allows a more flexibility in guiding light rays without the constraint of the material's refractive index and allow large splitting angle (in this example a very large splitting angle at 53° has been demonstrated). By using high speed CNC machining with proper lubrication and cooling system, a mirror like-surface is possible.

Hollow waveguides have been previously used in laser light delivery system for medical application [6, 7] where the radiation wavelengths used are greater than 2 μm [7]. These devices are also being used for photonics integrated circuits where temperature insensitivity is required [8].

Figure 5(a) shows the 3D CAD designs of the coupler showing the input POF fiber, the middle hollow taper waveguide and the output POF fibers. The core size for the POF coupler is 1 mm which allows low cost step index POF (SI POF) fiber with numerical aperture (NA) of 0.5 to be used for the device construction. The CAD designs as in Figure 5(a) are then combined to form a complete structure which will then be used for device simulation. Figure 5(b) shows the complete device structure after the individual CAD structures are combined.

The second 1×2 POF coupler design will be an acrylic-based coupler with an optical glue taper region. The POF coupler is constructed using acrylic substrate and UV curable optical glue filled into the taper waveguide region. The POF coupler is divided into three segments: An input POF fibers, middle taper waveguide region and output POF fibers. Similarly, the splitting angle of the POF coupler is set at 53°.

The cladding material is made of acrylic with RI of 1.49 as these acrylic materials are cheap material and can be easily obtained at any hardware stores. A large sheet of acrylic can be bought at a very



(a)

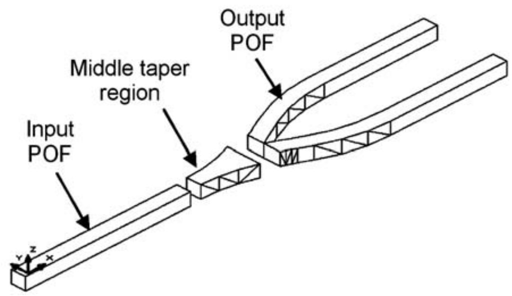
(b)

Figure 5. CAD design of the metal-based 1×2 POF coupler. (a) Input POF, middle hollow taper and output POF, (b) POF coupler after combining.

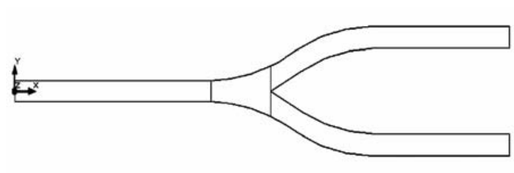
minimal cost and they can be easily cut and polished into small pieces. The material for the core is an optical glue which is used for bonding optical fibers. They are very cheap and come in many packaging forms such as syringes with different sizes of dispense needles. We are able to dispense these glue into our taper waveguide manually without the use of expensive dispensing tool. In addition, this optical glue can be easily cured using handheld UV source without the need of expensive lithography system.

4. NON SEQUENTIAL RAY TRACING

Due to the multimode characteristics of the device, non-sequential ray-tracing simulation tool has been used. Ray tracing simulation of the waveguide is performed to predict the optical transmission properties of the waveguide. In a non-sequential ray tracing, we use three dimensional (3D) object, which is pre-drawn using CAD tool.



(a)



(b)

Figure 6. CAD design of the acrylic-based 1 × 2 POF coupler. (a) Input POF, taper region, output POF, (b) POF coupler after combining.

For the metal-based POF coupler, the inner-surface of the hollow taper waveguide structure is defined as reflective where the material coating is written as metal coating. As for the input and output sections, an outer layer is defined to simulate the cladding for the POF fibers, where the refractive index for the core is defined as 1.49 and cladding as 1.0. We have set the cladding index to be 1.0 (air clad) as the actual cladding thickness will be negligible (about 20 µm) compare to the core diameter of 980 µm. The wavelength used in this simulation is 650 nm, with an input power of 1.0 mW. Another feature of this waveguide structure is that it is operated unidirectional only.

The ray tracing result for the metal-based 1 × 2 POF coupler is shown in Figure 7. It can be seen that light rays are confined completely in the POF coupler in all sections, input, output and the middle hollow taper region. The output power measured at the two output ports are 0.52 mW and 0.46 mW respectively. The insertion loss of this device is about 3 dB.

In order to have an idea of what occurs in the taper region, the following analyses are done in the simulation tool with some filtering of the optical rays. Figure 8 shows the close-up view ray tracing of the hollow taper region.

In the analysis of the metal-based hollow taper structure, we can

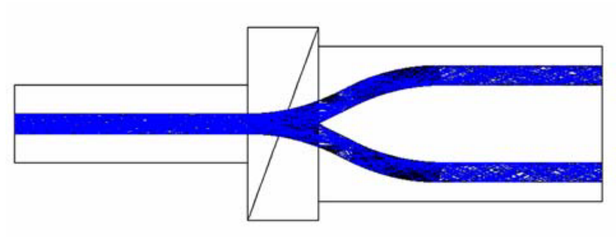


Figure 7. Ray tracing of the metal-based 1×2 POF coupler with a middle hollow taper waveguide.

determine if there are rays that transmit out of (or refract out) of the hollow region. Secondly, we can determine if there are rays that are not being reflected after striking or entering the hollow region. Thirdly, we can determine if there are rays being scattered or transmitted out (or refracted out) of the output branch POF fibers as soon as the rays leave the hollow taper region. All of these can be done by using filter strings in the simulation tool. These filter strings will allow us to observe any rays that satisfy the filter requirements. These results are shown in the following figures.

Based on these ray tracing analyses for the metal-based POF coupler, we conclude that all the rays that enter the hollow taper region are all confined in it without being scattered or refracted out of this region. The results also show that a small fraction of rays do not strike the inner surface of the hollow structure but just passing through it. These rays also contribute to guided rays in the waveguide. Hence, there is no loss associated with this device structure. Finally, we can see that all outgoing rays from the hollow taper region are all transmitted into the output branch POF fibers. For the second type, which is the acrylic-based POF coupler with an optical glue taper region, the non-sequential ray tracing is performed using the 3D design of the POF coupler in Figure 6(b). Before the ray trace can be performed, we have to define the claddings for the input, middle waveguide and output POF fibers. The claddings for the input and output POF fibers are set with a refractive index (RI) of $n = 1.0$ (actual value is 1.40). This approximation is made as the actual cladding of the POF fiber is only about 20 µm thick compare to the core of 980 µm. The core for the input POF and output POF has a RI of 1.49 which is the RI of a SI POF fiber.

The middle taper waveguide region has a different characteristics than that of the input and output POF fibers. Here, we will model the middle waveguide based on the actual substrate material used which

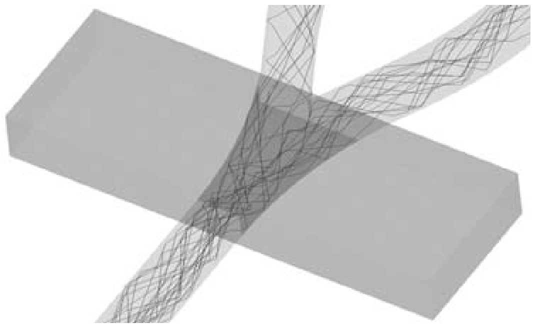


Figure 8. Close up view ray tracing of the metal-based hollow taper region.

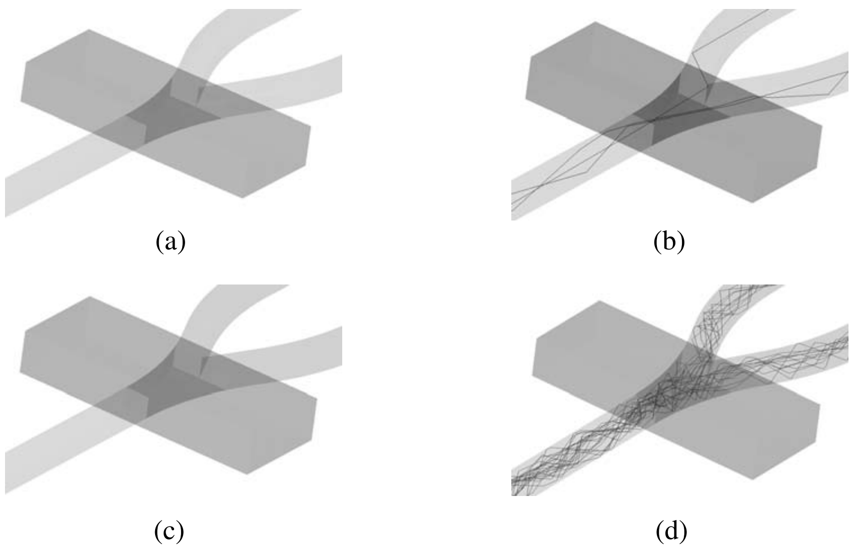


Figure 9. (a) No ray transmits out of (or refract out) of the hollow region (b) Rays that do not reflect on the inner surface of the middle taper region but pass through it (c) No scattering rays (d) Outgoing rays from the hollow taper region are all transmitted into the output branch POF fibers.

is an acrylic block with a RI of 1.49. The core of the middle waveguide will be fabricated using a low-cost UV curable optical glue which is normally used for bonding glass or fiber optics components. It has a RI of 1.56 and can be easily cured when expose to UV light. The layout of the 1×2 POF coupler is shown in Figure 10. The wavelength

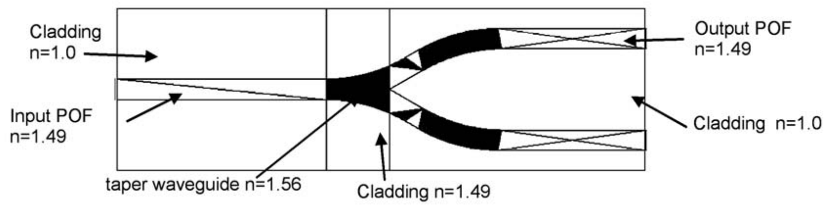


Figure 10. Acrylic-based 1×2 POF coupler block layout for ray tracing.

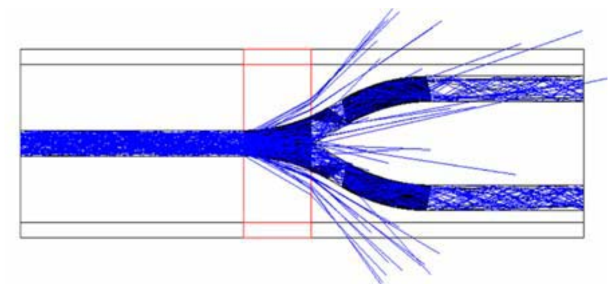


Figure 11. Ray tracing of the acrylic-based 1×2 POF coupler.

used in this simulation is 650 nm, with an input power of 1.0 mW.

The ray tracing diagram of the acrylic-based 1×2 POF coupler is shown in Figure 11. Photodetectors are positioned at both output ports of the device. The output power for the POF couplers has been obtained from the ray tracing plot. The output signal measured at the output ports of the 1×2 POF coupler is 0.24 mW and 0.25 mW. The insertion loss of this device is about 6 dB whereas the excess loss of this device is about 3 dB.

We can perform the same analysis to the acrylic-based POF coupler. Figure 12 shows the close-up view ray tracing of the acrylic-based taper region.

In the analysis of the acrylic-based taper region structure, we can determine if there are rays that are being transmitted out or leaks out of the middle taper region and transmitted into the middle cladding. Secondly, we can determine if there are rays that are not being reflected after striking or entering the taper region. All of these can be done by using filter strings in the simulation tool. These filter strings will allow us to observe any rays that satisfy the filter requirements. These results are shown in the following figures.

Figure 13(a) shows that a small fraction of rays escape or transmit out of the middle taper core region. These rays contribute to the loss

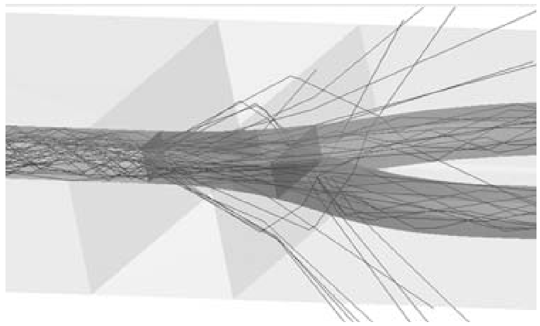
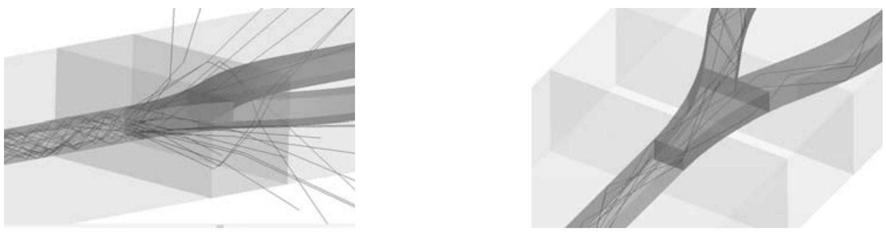


Figure 12. Close up view ray tracing of the acrylic-based taper region.



(a) (b)

Figure 13. (a) Rays leaks out or transmit out of the middle taper core region. (b) Rays that do not reflect on the inner surface of the middle taper region but pass through it.

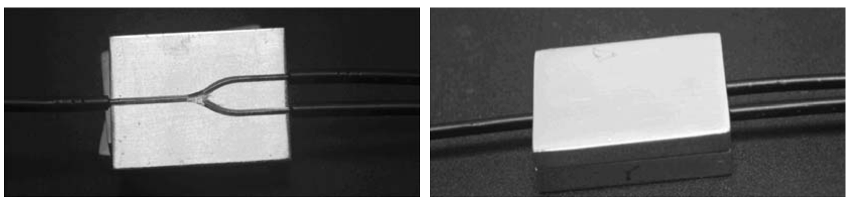
of the device system. Similarly, Figure 13(b) shows a small fraction of rays do not strike the inner surface of the taper region but just passing through it. These rays contribute to the guided rays in the waveguide.

5. DEVICE FABRICATION AND MEASUREMENT

There have been many techniques of assembling POF couplers. These techniques include (i) twisting and fusion (ii) side polishing (iii) chemical etching (iv) cutting and gluing (v) thermal deformation (vi) molding (viii) biconical body and (ix) reflective body [1].

One of the key advantage of the newly developed waveguide coupler is the simplification of the fabrication steps. In this process, a rigid mold insert is designed and fabricated using a CNC machining tool. This technique is a maskless process which significantly reduced the highly cost of producing photomask, and the costly photolithographic equipment. Modern micro engraving tools can easily produce the mold inserts, easy to operate and low cost. After the mold insert has been fabricated, short POF fibers are inserted into the grooves until the fibers are positioned just before the waveguide taper region.

For the metal-based POF coupler, we have used aluminum blocks for the mold insert. A CNC milling machine with tool size of up to 0.5 mm and spindle speed up to 8,000 rpm has been utilized. A short 1.0 mm core POF fiber is used for the input and output ports. Figure 14(a) shows the 1×2 POF coupler with the short POF fiber inserted into the engraved region of the mold insert. Figure 14(b) is the POF coupler with a top metal plate.



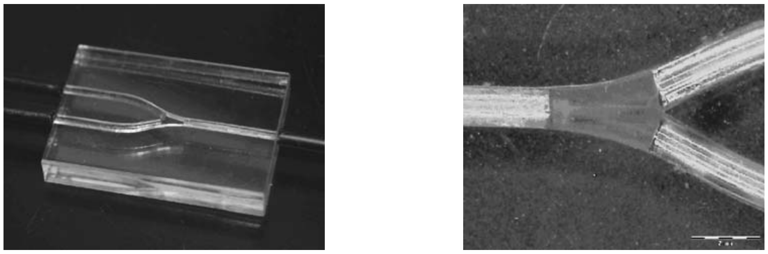
(a) (b)

Figure 14. Fabricated metallic-based 1×2 POF coupler devices (a) Y-branch coupler (b) coupler with top metal plate.

The optical power from the POF coupler output ports have been measured using Advanced Fiber Solution FF-OS417 (LED) and optical power meter OM210. The test wavelength is set at 650 nm. The effective input power P_{in} is 0 dBm. The output power detected at both output ports are $P_1 = -8.2$ dB and $P_2 = -7.75$ dB. The insertion loss of this device is about 8.2 dB and the excess loss is 4.96 dB.

Similarly, for the acrylic-based POF coupler, a rigid mold insert is designed and fabricated using a CNC engraving tool. We have used acrylic (PMMA) material as the substrate and cladding for the waveguide taper region. The RI of the acrylic material used is about 1.49.

Milling tool size of 0.5 mm is used and spindle speed of 15,000 rpm and feed rate of 5 mm/sec have been utilized. After the mold insert has been fabricated, short SI POF fibers (10 cm) are inserted into the grooves (input and output ports) until the fibers are positioned just before the waveguide taper region. Norland NOA-71 UV curable glue is used as the main core material inside the taper waveguide region. We have inserted this material using a small syringe and UV-cured it for 10 minutes using a 200 W UV exposure system. The cured UV glue has a RI of 1.56. The 1×2 POF coupler which has been fabricated



(a) (b)

Figure 15. Fabricated acrylic-based 1×2 POF coupler (a) assembled coupler with POF fibers (b) coupler showing the middle taper waveguide region and the input and output POF fibers.

and assembled showing the input and output POF fibers and the taper waveguide region is shown in Figure 15.

The insertion loss of this device has been tested using Advanced Fiber Solution FF-OS417 (LED) and optical meter OM210. The test wavelength is set at 650 nm. The effective input power P_{in} is 0 dBm. The output power detected at both output ports are $P_1 = -8.1\,\text{dB}$ and $P_2 = -7.13\,\text{dB}$. The insertion loss of this device is about 8.1 dB and the excess loss is 4.58 dB. The high loss is expected based on the simulation result which gives an insertion loss of about 6 dB.

The 1×2 POF coupler which has been fabricated here may be an alternative to that of the 1×2 POF coupler which was fabricated by IMM (*Institut für Mikrotechnik Mainz*) in Germany. The insertion loss of the device by IMM is about 6 dB [9]. The fabrication technique requires several additional steps including laser machining using excimer laser for PMMA resist patterning and injection molding for molding.

A similar device with circular cross section has also been fabricated by Takezawa et al. [10] which showed low excess loss (1.91 dB). Nevertheless, the device requires the use of injection molding tool which can increase the cost of making these devices.

Another Y-branch device has been designed and fabricated by Mizuno et al. [11]. This device fabricated using hot embossing technique requires additional steps to produce the silicon rubber mold. The silicone rubber mold has to be made using photoresist master and hence additional cost on the photolithography step. The use of hot embossing meaning high temperature process is required for pressing the under cladding PMMA material against a resin stamper which is also made by hot embossing using the silicon mold. Even with an excess loss of of 1.75 dB at a splitting angle of 12°, the production cost will still be high compared to our process which only requires producing the metallic-mold insert using simple CNC machining.

Using the proposed metal-based hollow waveguide structure, we are able to produce device with large splitting angle without the loss associated with the branching angle.

6. CONCLUSIONS

Low cost 1×2 POF Y-branch coupler with a taper waveguide region has been designed and fabricated. This device is part of our work on optical code generating device for an optical access-card system. The POF coupler has been fabricated using low cost aluminum and acrylic based materials and fabricated using a desktop CNC machining system. The device structure is composed of input POF fiber, middle taper waveguide and output POF fibers. The insertion loss of the metal-based device is still high at 8.2 dB. Due to the excessive surface roughness on the metallic surface, high loss are unavoidable in the hollow taper waveguide region. In addition, due to back-reflection and unmatched NA at the POF fiber-hollow taper interface, high coupling loss is expected. Similarly, for the acrylic-based device, an insertion loss of about 8.1 dB has been obtained. The high insertion loss is due to the structure of the Y-branch coupler design especially on the taper waveguide region. Coupling loss especially due to the surface roughness at the interface of the POF fibers and waveguide taper region and the uneven coupling between the rectangular-shaped taper region and the circular-shaped POF fibers may have also contributed to the high device loss in the waveguide region.

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