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PLASTIC OPTICAL FIBER COUPLER WITH HIGH INDEX CONTRAST WAVEGUIDE TAPER

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Abstract—A simple low-cost Y-branch plastic optical fiber (POF) coupler which can be assembled easily by the end users has been developed. The acrylic-based Y-Branch POF coupler consists of input POF fiber, a middle high index contrast waveguide taper and output POF fibers. The optical device is based on a 1×2 Y-branch coupler design with a middle high index contrast waveguide taper. Non-sequential ray tracing has been performed on the device giving an insertion loss of 4.68 dB and coupling ratio of 50 : 50. The middle waveguide taper region is constructed on the acrylic block itself without using any additional optical waveguiding medium injected into the engraved taper region. Fabrication of the devices is done by producing the device structures on an acrylic block using high speed CNC machining tool. Input and output POF fibers are inserted in to this device structure in such a way that they are passively aligned to the middle waveguide taper structure. The first prototype device shows an insertion loss of 7.5 dB and a splitting ratio of 50 : 50. A second prototype device which includes additional U-groove slots for the jacketed fibers shows an insertion loss of 5.9 dB and a splitting ratio of 50 : 50.

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1. INTRODUCTION

A new type of optical fiber, namely the Plastic Optical Fiber (POF), has been around for nearly 30 years. Due to its high attenuation and the lack of demand of specific commercial applications, POF has remained rather stagnated for years. However, a lot of interest on POF has been received, which gives rise to a great deal of applications since the invention of the graded-index plastic optical fibers by Professor Koike at Keio University (1990) and the development of the low attenuation perfluorinated fibers (1996) [1]. POF is currently a well known medium for short range data communication due to its large-core size, multimode properties, low cost and robust characteristics. It is also being utilized in the automotive, entertainment, sensors, lighting and decoration system [2]. In all of these applications, it is sometimes necessary to split or combine the optical signals using passive components.

Y-branch type POF couplers are of great importance in these applications for splitting and coupling of light signals. Fiber-based Y-branch couplers are normally constructed by polishing two fibers and gluing them together [3]. It is the cheapest and easiest technique of producing low cost POF couplers. Even though the cost of producing these couplers is low nevertheless the main disadvantage of this technique is that non-symmetrical coupler will be difficult to produce.

Works on planar-waveguide based symmetrical Y-branch POF couplers with core sizes of 1000 μm have been previously reported by Mizuno et al. [4], Klotzbuecher et al. [5] and Takezawa et al. [6]. All of these devices have utilized branching angle of less than 10°. For example, Mizuno et al. used hot embossing techniques where the fabrication technique involves three major steps: (i) fabrication of stamper for use in hot embossing, (ii) hot embossing for fabricating the under cladding, and (iii) fabrication of core and top cladding region. The core material is made from UV-curable epoxy resin whereas the claddings are made from Poly(methylmethacrylate) (PMMA) material. The insertion loss was recorded at a value of 4.0 dB. Klotzbuecher et al. reported another Y-branch POF coupler with core size of 1000 μm. This coupler was fabricated using laser-LIGA and micro-injection technique. The device fabrication requires the mold insert to be prepared using the laser-LIGA technique which utilizes the excimer laser for laser ablation. A small syringe is then used to inject the photo-curable resin into the grooves. The device has problem with light scattering from the bubbles formed in the core region during the curing process. The best value for the insertion loss of this device was reported at 5.6 dB. Finally, the device fabricated by Takezawa et al. is another Y-branch POF coupler based on planar waveguide technology. Here, they have adopted injection molding technique to fabricate the devices. The mold insert was fabricated using mechanical technique. The core and the cladding are basically polymer material suitable for injection molding. This device has an insertion of 4.41 dB. Nevertheless, all of these devices required expensive production equipment and in-factory precision assembly tools. In addition, these devices are unsuitable for a 'do-it-yourself' (DIY) optical device.

In this paper, we provide analyses on a new design of an acrylic-based 1×2 Y-branch POF coupler. A high index contrast waveguide taper structure has been incorporated with this device which allows not only a passive alignment structure but has improved the insertion loss of this design compare to the previous 1×2 Y-branch POF coupler designs. The high index contrast waveguide taper enables the device to have large splitting angle and hence shorter device length. The device presented here is one of the developed POF devices which are currently being developed. Previous coupler designs include an acrylic-based POF coupler with NOA71 polymer waveguide taper with insertion loss of 8 dB [7]. In this design, the POF coupler has a middle waveguide taper made of UV curable glue. Device structure has been fabricated using CNC machining with a groove opening of 1 mm which allows the 1 mm core size POF to be slotted into the engraved U-grooves. Norland NOA-71 UV curable glue is injected into the waveguide taper region and cured using UV exposure source. The second design is also an acrylic-based POF coupler but using Norland NOA63 UV curable glue. This device has an insertion loss of 7.8 dB [8]. Another design structure is an acrylic-based POF coupler but with a hollow waveguide taper. The device is composed of three segment: an input POF fiber, an intermediate hollow taper waveguide and output POF fibers. Short POF fibers at the input and output ends are inserted into the engraved U-grooves before the interfaces of the hollow taper waveguide. This device has an insertion loss of 10.5 dB [9]. The high loss is expected due to high cladding absorption causes by the suppression of the higher order modes in the hollow taper waveguide region. A metal-based device has also been constructed using aluminum block. The device is composed of three sections: an input POF fiber, an intermediate hollow waveguide taper and output POF fibers. Fabrication of the device is done by producing the mold insert using CNC machining tool and short POF fibers at the input and output sections are inserted inside the mold insert before the interfaces of the hollow waveguide taper. The middle metal hollow structure allows wave guiding to occur by simple reflection on the metallic inner-surface. The insertion losses of

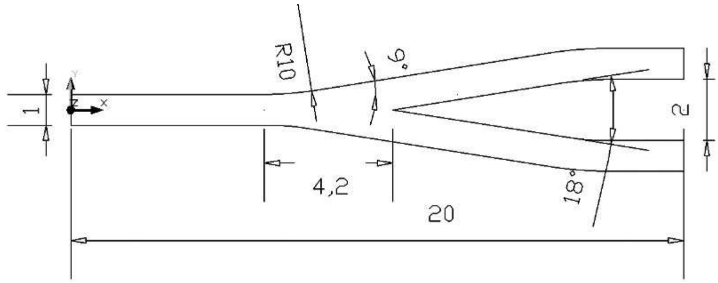


Figure 1. 1×2 Y-Branch POF coupler design layout.

these metal-based POF coupler are recorded at 8 dB [10] and 5.8 dB [11] respectively.

2. DEVICE DESIGN

The newly developed devices are constructed using blocks where designed structure is engraved onto these blocks or mold inserts. The POF coupler design will utilize a simple 1×2 Y-branch structure which is shown in Figure 1. One of the important features of the Y-branch coupler is the region between the input port and the two branch output ports, which is the splitting section of this device. In order to have the two output branches to have the same width size as the input port, a waveguide taper is required.

For a highly multimode device, a large divergence angle will cause some of the higher order modes to transform into cladding modes and some become leaky modes as they penetrate out of the waveguide. This result in high radiation loss and causes higher attenuation. Hence, for low attenuation Y-branch coupler, a small splitting angle will be used. However, the use of small splitting angle will lead to an unacceptably long device. This strict requirement on the size of the splitting angle normally applies to the conventional waveguide using two different materials for the core and cladding section (two different refractive indices). Conventionally, to allow for large splitting angle with low radiation loss, a high refractive index contrast system will be required [12].

In this coupler design, a two refractive-index system will be used for device design. In a two refractive-index system where the core and cladding are defined by a refractive index n_{co} and n_{cl} respectively, some design analysis have to be considered for optimum waveguide taper length, d. Beltrami [13] provided a comprehensive analysis on the optimum taper length in a two refractive-index system for a Y-

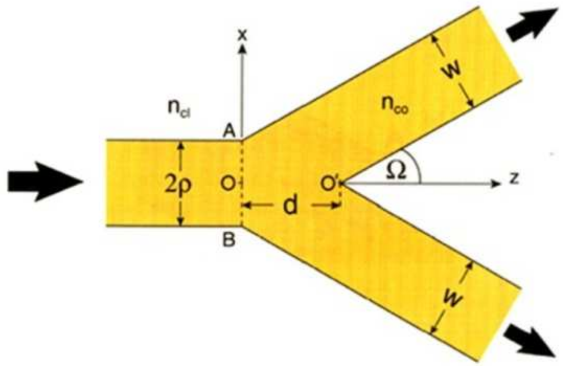


Figure 2. Geometrical structure of a symmetric Y-junction multimode device [13].

junction multimode waveguide.

Figure 2 shows the geometrical structure of a symmetric Y-junction device used in the analysis for the taper length, d. Beltrami [13] has shown that for a lossless Y-junction, the branching angle, Ω must be within the specified value as shown below,

$$\Omega \leq \frac{\theta_c D}{D+1} \tag{1}$$

where θ_c is the complimentary critical angle, given by the following relationship [13],

$$\theta_c = \sin^{-1}\left\{\frac{\left(n_{co}^2 - n_{cl}^2\right)^{1/2}}{n_{co}}\right\} \tag{2}$$

D is the normalized value of d and D is defined by the following equation [13],

$$D = \frac{d \sin\Omega}{\rho(2-\cos\Omega)} \tag{3}$$

where d is waveguide taper length, Ω is the branching angle, and ρ is the waveguide half-diameter.

Hence, for the Y-branch device design with a two refractive-index system and output waveguide width, w equals to 2ρ will have its branching angle, Ω limited to half the critical angle or $\theta_c/2$. In a 1 mm core step index (SI) POF fiber system where numerical aperture (NA) is 0.5, ρ is 0.5 mm, D is 1 (2ρ), core refractive index, n_{co} is 1.49 and cladding refractive index n_{cl} is 1.40, the critical angle, θ_c is 20°. Therefore, the branching angle, Ω is limited to 10° only. The

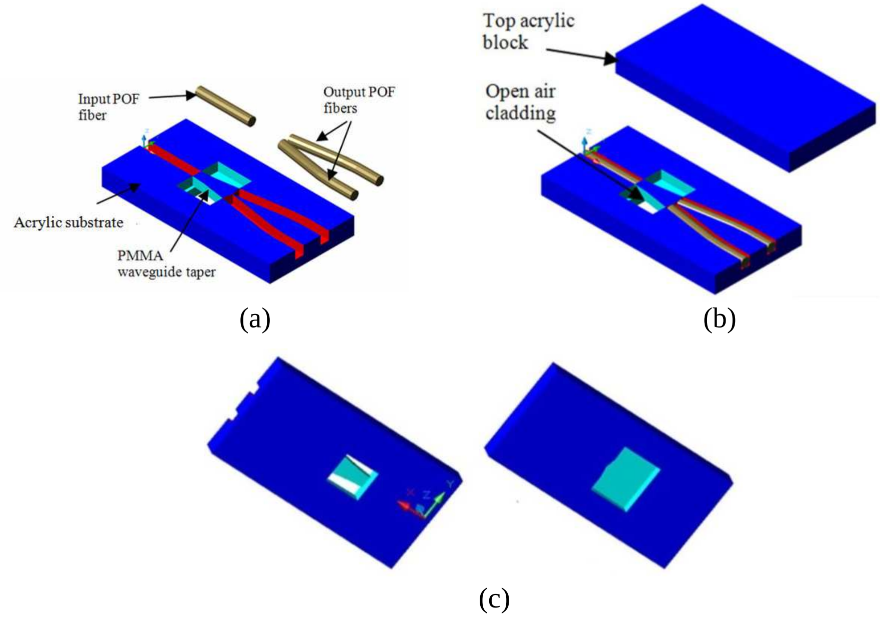


Figure 3. Acrylic-based Y-branch coupler: (a) Design layout. (b) Device assembly. (c) Void regions for bottom (device structure) and top acrylic blocks.

minimum required taper length, obtained by solving Equation (3) for the branching angle of 10° is about 2.9 mm.

The acrylic-based Y-branch design, is composed of three sections: an input POF fiber, middle high index contrast waveguide taper region and output POF fibers. The input and output unjacketed POF fibers are inserted into the engraved U-groove slots on the device structure in such a way that they are passively aligned to the middle waveguide taper structure. The U-grooves are designed with square cross sections which allow the 1 mm sized POF fibers to fit into these slots. Figure 3(a) shows the design layout of the acrylic-based POF coupler showing the individual components for the device construction. Figure 3(b) shows how the complete device is constructed by enclosing it with another top acrylic block. The unique feature of this device is the middle acrylic (PMMA) waveguide taper with its refractive index (R.I.), n_{co} of 1.49 and surrounded by an open air cladding with R.I., n_{cl} of 1.0. This design allows the waveguide taper to be a high index contrast structure and enables large splitting angle. Hence, for this Y-branch device design with a two refractive-index system with core width 1 mm (2ρ), n_{co} is 1.49 and n_{cl} is 1.0, the critical angle, θ_c is enormously at 47°. Therefore, the branching angle, Ω can be designed up to 23.5°. The minimum taper length for this branching angle of 23.5° can be set down to 0.9 mm. In order to ensure the waveguide taper has an all-air cladding structure as per-design, the top enclosing block is also constructed in such a way that the region enclosing the waveguide taper has small hollow region, as shown in Figure 3(c). In Figure 3(c), the bottom of the device block with the waveguide taper has a hollow region at the bottom and similarly the top enclosing block has also a small hollow region. These structures will ensure that the waveguide taper is surrounded by an air-cladding.

3. DEVICE SIMULATION

Ray-tracing technique has been used to model the optical devices due to the multimode characteristics of the POF coupler. The modeling of the POF couplers is done using *non-sequential* ray tracing in Zemax. In a non-sequential ray tracing, we use three dimensional (3D) object, which is pre-drawn using computer aided design (CAD) tool.

In this device model, based on the structure in Figure 3(a), we have included some real device structure properties which include cylindrical-shaped POF fibers. In addition, real model for SI POF fibers with core diameter of 980 μm and a cladding layer of 20 μm thickness have also been defined. The splitting angle, which is twice the branching angle value is at 18° based on the Y-branch design structure in Figure 1.

The model used for simulation includes the bottom device block, the top enclosing block, and the POF fibers which are made of the fiber core and fiber cladding. The device block is the acrylic block where the Y-branch design will be engraved onto it. The top enclosing block is the acrylic block for enclosing the device. Both blocks are defined as acrylic or PMMA material with R.I. set at 1.49. The fiber core is a cylindrical-shaped structure with a diameter of 980 μm while fiber cladding is a cylindrical-shaped structure with a hollow region in the middle. The cladding is 20 μm thick which represents the actual SI POF fiber cladding thickness. The R.I. for the fiber core is defined as 1.49 and the cladding as 1.42. Both the core and cladding when combine will represent a 1 mm sized SI POF fiber.

Figure 4(a) shows the 3D layout used in the device simulation. The 2D ray tracing result shown in Figure 4(b) illustrates how the high index contrast waveguide taper successfully function as an optical splitter and allows propagation of light rays with minimum loss due to radiation. The optical source used in the simulation is from a

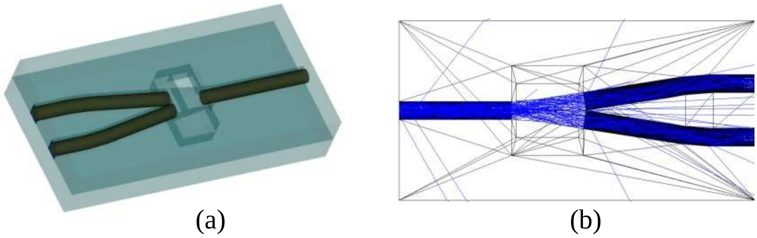


Figure 4. Device simulation. (a) 3D CAD device layout. (b) 2D ray tracing of the POF coupler.

rectangular source with a wavelength of 650 nm, and optical input power of 1.0 mW. The insertion loss at the two output ports are 4.68 dB respectively with an excess loss of 1.68 dB and very good splitting ratio of 50 : 50.

4. DEVICE FABRICATION AND ASSEMBLING

The newly developed POF coupler has one major advantage which is the simplification of the fabrication steps. In this process, the designed structures are engraved onto the acrylic block using a computer numerical control (CNC) machining tool. This technique is a maskless process which significantly reduced the highly cost of producing photomask, and the costly photolithographic equipment. In this project, Roland's EGX-400 desktop CNC engraver machine has been utilized to engrave the device design structure done in CAD tool onto the substrates. Milling tool size of 1.0 mm is used and spindle speed of 15,000 rpm (revolution per minute) has been utilized. The milling tool used is a 2-flute, 30° *Helix* shape endmill tool. The outer diameter of the endmill tool is 1.0 mm. The accuracy of the cutting is preset using the CAD/CAM software at about 0.001 mm. Nevertheless, due to the large size of the POF fiber, small deviation on the waveguide diameter can be tolerated. A more important and critical parameter on the device structure will be the surface finishing of the waveguide taper surface.

Prior to engraving, the device machining process is simulated using the CAD/CAM simulation tool. The simulated result of the design is shown in Figure 5(a). The result shows that at the input and output of the waveguide taper, the end structure is not straight but has a curvature. This is due to the machining process where the endmill tool does not have a square cross section but rather having a circular cross section. This curvature will cause an air gap between the POF

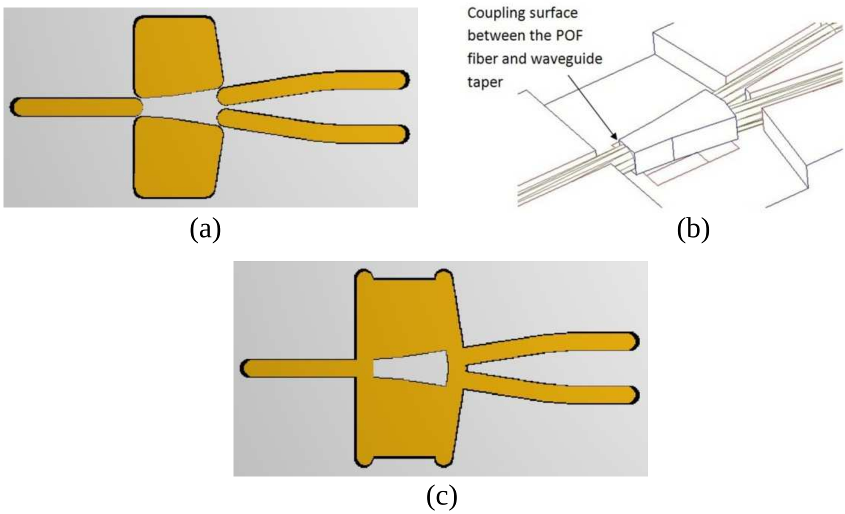
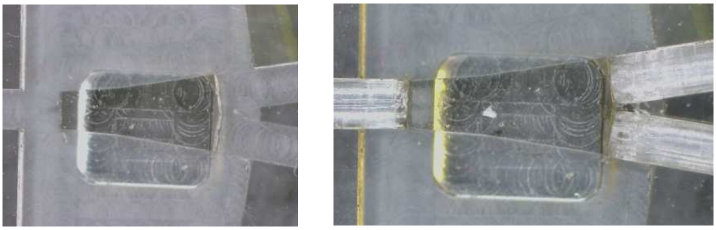


Figure 5. Optimization of the coupling surface of the waveguide taper. (a) Model before optimization. (b) Close view of coupling surface. (c) Model after optimization.

fibers, whose end surface is flat and the waveguide taper. Figure 5(b) shows the required coupling surfaces between the POF fibers and the waveguide taper. The end surfaces of both the fibers and the waveguide taper have to be flat. A simple modification to the design allows this problem to be solved. Two lines are plotted perpendicularly at both ends of the waveguide taper structure. These plotted lines will create a flat surface to the input and output ports of the waveguide taper. The simulated design with the additional plotted lines is shown in Figure 5(c).

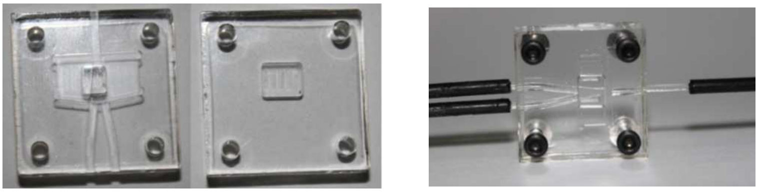
After the device structure has been engraved, short SI POF fibers are inserted into the engraved slots (input and output ports) until the input and output POF fibers are positioned at the required position at the waveguide taper region. Figure 6(a) shows the close-up view of the engraved waveguide taper region prior to fibers insertion. Figure 6(b) shows the device with the input and output POF fibers positioned into the engraved U-groove slots and butt-coupled to the waveguide taper. Figure 7(a) shows the device block and the top enclosing block. Figure 7(b) is the assembled acrylic device showing the POF fibers are properly inserted into the input and output ports and butt-coupled to the waveguide taper.

The insertion loss of this device has been tested at a wavelength



(a) (b)

Figure 6. Close-up view of the device block with the engraved design structure. (a) Before fiber insertion. (b) POF fibers positioned and aligned with the middle waveguide taper structure.

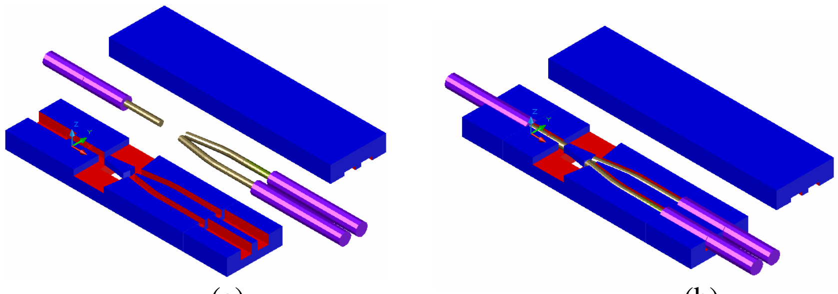


(a) (b)

Figure 7. Fabricated acrylic-based 1×2 Y-branch coupler. (a) Device block and top enclosing block. (b) Assembled device.

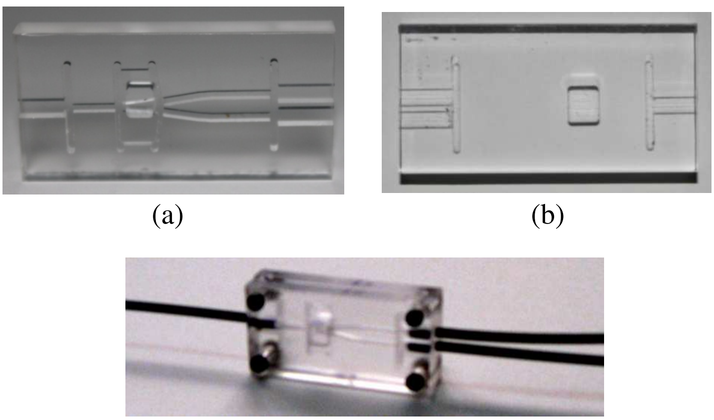
of 650 nm using Advanced Fiber Solution's FF-OS417 LED source and OM210 optical power meter. The effective input power is 0 dBm. The insertion loss of the device is about 7.5 dB and with an excess loss of 4.5 dB while the coupling ratio is at 50 : 50.

A second version of the device has been developed which include an improvement to device assembling and packaging. In this second prototype, U-groove slots for the jacketed POF fibers are added. These grooves allow the POF fibers to be firmly secured at the input and output ports. Due to the friction between the jacketed fibers and the engraved acrylic surface, the fibers are tightly secured and non-movable. This will ensure the coupling end of the POF fibers close to the waveguide taper will not be subjected to unnecessary movement. The CAD layout of the second prototype device is shown in Figure 8(a) prior to fibers insertion and Figure 8(b) after fibers insertion. Figures 9(a), (b) and (c) show the device block, the top enclosing block and the assembled device respectively. In this second prototype, the larger U-groove slots are designed which enable the 2.2 mm jacketed fibers to fit firmly in these slots. Similarly, the second prototype device has been tested for its insertion loss. The insertion



(a) (b)

Figure 8. Design layout for the second prototype device. (a) Device before fibers insertion. (b) Device after fibers insertion.



(a) (b)

(c)

Figure 9. Fabricated acrylic-based 1×2 Y-branch coupler with additional U-groove slots. (a) Device block. (b) Top enclosing block. (c) Assembled device.

loss of the device has improved to a value of 5.9 dB with an excess loss of 2.9 dB while the coupling ratio remains at 50 : 50.

The fabricated devices have higher insertion loss compare to that of the model device, about 4.68 dB. One of the major contribution to the loss is the coupling loss between the fibers and the waveguide taper. The end surfaces of the fibers and the waveguide taper have to be highly flat with minimum surface roughness. Surface roughness on the end surfaces of the waveguide taper will introduce air gaps which will increase the coupling loss. Improvement to the surface roughness can be done by optimizing the machining steps which include using lubricants for engraving, higher spindle speed and reducing the machine feed rates [14]. In addition, coupling loss can be improved by introducing an index matching gel between the POF fibers and the waveguide taper.

It has been mentioned earlier that the fiber-based Y-branch couplers are the cheapest and easiest technique of producing low cost POF couplers. Even though the cost of producing these couplers is low nevertheless the main disadvantage of this technique is that non-symmetrical coupler will be difficult to produce. The newly developed device has a major unique advantage where it enables a non-symmetrical coupling ratios device to be constructed by solely exploiting the simple theory of attenuation between two separated fibers. The theory behind the non-symmetrical coupling ratio lies in the following principle of attenuation between two separated fibers. The attenuation caused by the lateral displacement of two fibers is shown in Figure 10.

The movable fibers can be positioned at the output port of the Y-branch structure which is illustrated in Figure 11. By moving the output fibers at a required distance, the output power can be

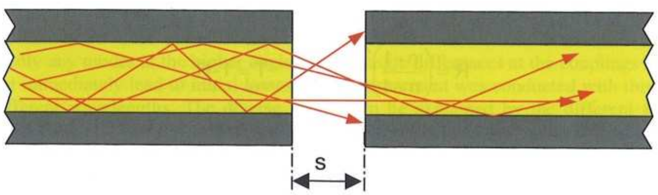


Figure 10. Attenuation induced by lateral displacement of two fibers [15].

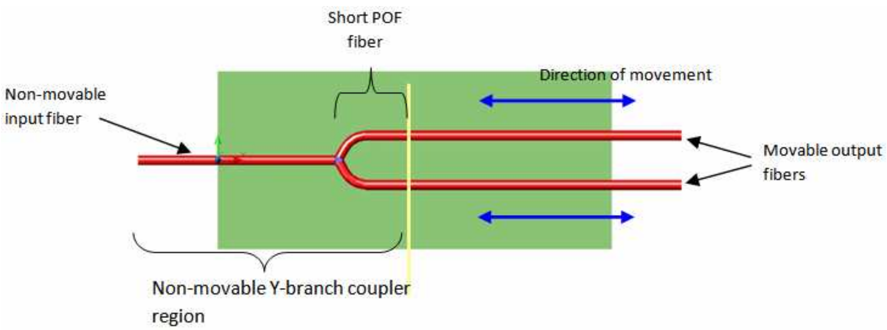


Figure 11. POF coupler with Y-branch structure design and movable output fibers.

attenuated. If only one fiber is moved while the other fiber is fix, then a non-symmetrical coupling ratio device can be constructed easily.

5. CONCLUSIONS

The POF coupler presented here is a potential optical device for the next generation 'do-it yourself' optical component. This device eliminates the used of sophisticated production equipment and technically skilled manpower for device fabrication and assembling. The device which is based on low cost acrylic material has been designed with a high index contrast waveguide taper. Modeling of the device has been performed both at the device level using an optical simulator tool and at the CAD/CAM level prior to machining. Optimization of the design has been performed at the CAD/CAM stage to allow an improvement to the fiber-waveguide taper coupling. The manufacturing of the component has been done using EGX400 desktop engraver system. The first prototype device showed an insertion loss of 7.5 dB and coupling ratio of 50 : 50 whereas the second prototype device with additional slot for the jacketed fibers showed the insertion loss dropped to 5.9 dB and maintaining the coupling ratio at 50 : 50. The reduction of the insertion loss makes this device comparable to that of the previous develop devices based on metal hollow waveguide taper structure which sees the loss at 5.8 dB. These acrylic-based devices can be easily manufactured using low cost plastic injection molding tool.

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