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VARIABLE COUPLING RATIO Y-BRANCH PLASTIC OPTICAL FIBER (POF) COUPLER WITH SUSPENDED WAVEGUIDE TAPER

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Abstract—A variable coupling ratio Y-Branch plastic optical fiber (POF) coupler based on acrylic has been developed. This device utilized two optical designs: a Y-branch structure with a novel suspended waveguide taper and a simple attenuation technique based on lateral displacement of two fibers for the non-symmetrical coupling ratios. The high index contrast waveguide taper is constructed on the acrylic block itself where the area surrounding the waveguide taper has been designed in such a way that it is surrounded by an open air. A simple attenuation technique based on lateral displacement of two adjoining fibers for each of the two output ports has been proposed and presented for the non-symmetrical coupling ratios. Lateral displacement of the fiber is set from 4.4 mm down to 1.6 mm for output fiber 1 and 0.1 mm to 1.0 mm for output port 2. Numerical analysis has been done on the lateral displacement of the output fibers which shows the device is able to generate non-symmetrical coupling ratios. Device modeling has been performed using non-sequential ray tracing technique on the Y-branch coupler performing as a 3 dB coupler with an excess loss of 1.84 dB and a coupling ratio of 50 : 50. The designed coupling ratios vary from 1% to 45% for port 1 and 99% down to 55% for port 2 whereas in the simulated device, ratios vary from 7.65% to 39.85% for port 1 and from 92.35% down to 60.15% for port 2. Fabrication of the device is done by producing the device structures on an acrylic block using high speed CNC machining tool. The fabricated device has an excess loss of 5.85 dB while the coupling ratios are 56.86% and 43.14% when operating as a 3 dB coupler. In the

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variable coupling ratio mode, the coupling ratios are 10.09% to 32.88% for port 1 and 89.91% down to 67.12% for port 2. The excess loss of the fabricated device varies from 5.85 dB to 8.49 dB.

1. INTRODUCTION

Components for plastic optical fiber (POF) can be categorized into two parts: passive and active components. Passive components include connectors, couplers and splitters, filters and attenuators, mode mixers and converters, and other related passive devices [1] whereas transmitters and receivers are categorized as active components. Passive components cover a more vast area of the POF technology than that of active components. These passive optical devices, especially POF couplers are of great interest for applications in short length networks, such as in-home and in vehicle network, optical sensors, video-over POF, automobile multimedia system and in-flight entertainment systems. In all of the POF applications, it is necessary to split or combine the optical signals using these POF couplers.

Y-branch couplers are the simplest type optical splitting device used in these applications. The fiber-based Y-branch couplers are normally constructed by polishing two fibers and gluing them together. It is the cheapest and easiest technique of producing low cost POF couplers but it is normally fixed at 50 : 50 coupling ratios as it is difficult to fabricate asymmetric coupler with polishing technique. In addition, the polished-type coupler would not be able to function as variable coupler due to its production and assembling technique.

As for the planar waveguide based couplers, several types of symmetrical coupling ratios Ybranch couplers have been reported. These planar waveguide based couplers with core diameter of 1000 μm have been developed by others which include Mizuno et al. [2], Klotzbuecher et al. [3] and Takezawa et al. [4]. They have reported an excess loss of 1.0 dB, 2.6 dB and 1.41 dB respectively [2–4]. These devices utilized mold inserts which have been fabricated using hot embossing, laser-LIGA and injection molding techniques. As for the core materials, they are made from UV-curable epoxy resin and photocurable resin polymers suitable for injection molding. However, all of these devices required expensive production equipment and in-factory precision assembly tools. In addition, a low cost metal-based symmetrical coupling-ratio Y-branch POF coupler constructed using hollow waveguide taper structure has also been developed by us which provided an excess loss of 5 dB [5].

In addition to the symmetrical ratio couplers, non-symmetrical coupling ratios devices have also been reported. The device reported by

Suzuki et al. [6] is a single mode Y-branch coupler with the center axis of the branching output waveguide and the center axis of the waveguide taper shifted from each other. Kurokawa et al. [7] have developed a multimode Y-branch waveguide device where it used reflection at the reflecting surface of the waveguide to divide the optical power asymmetrically. Lin et al. [8] used micro prisms for their asymmetric single mode Ybranch coupler. The asymmetric multimode waveguide coupler developed by Love and Henry [9] utilized the geometry size of the output branch to control the power splitting ratios. Furthermore, a metal-based version of the asymmetric coupler developed using a complete hollow waveguide structure was also presented [10]. The design was based on an asymmetric Y-junction splitter [9] where the geometrical size of one output branch or the tap line was varied. The coupling ratios or TOFR (tap-off ratio) obtained based on the variation of tap line width are from 10.7% to 89.3%, for a tap width of 500 µm to 1 mm. The excess loss varied from 9.49 dB to 11.51 dB [10, 11].

All of these devices that have been reported are based on fixed and non-variable coupling ratios. There will be some applications which require the attenuation of light to be varied, especially in signal measurement applications. This so-called variable coupler can be inserted into a fiber link and allows variable light intensity. Two of the simplest attenuating techniques for optical fiber are based on the lateral and axial misalignment of two fibers. These two techniques are shown in Figure 1.

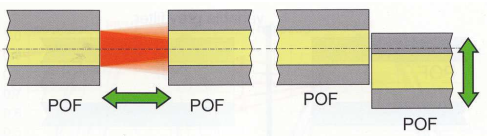


Figure 1. Fiber attenuation by lateral and axial fiber misalignment [1].

In addition to these two techniques, a variable POF coupler has been developed based on mode transition using bending fibers. The variable POF coupler by developed Kagami et al. [12] is designed based on changing the bending radius of the POF fiber, shown in Figure 2. This device is constructed using POF fibers and one of the POF fiber is bent using a push-rod. The bending of this fiber causes the core mode fields of the POF fiber to be converted into cladding mode fields. These cladding mode fields are then tap out by another POF fiber.

The work demonstrated in this paper showed how a low cost acrylic-based variable coupling ratio Y-branch POF coupler can be implemented using a single structure Y-branch. The new proposed

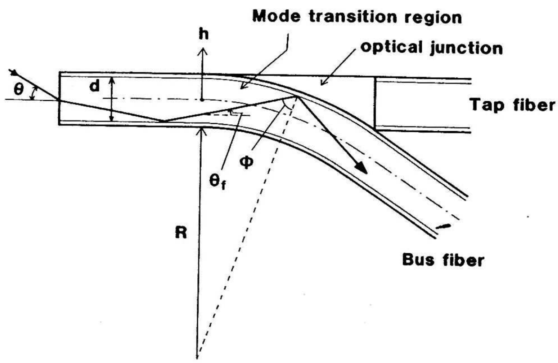


Figure 2. Schematic diagram of the variable POF coupler showing the mode transition region [12].

device will reduce the cost of having separate and bulky external variable attenuators attached to a standalone symmetrical Y-branch coupler. The POF device is constructed using acrylic substrate material. This device utilized two optical designs: a novel suspended waveguide taper and simple attenuation technique based on lateral displacement of two fibers for the non-symmetrical coupling ratios. Devices are modelled using non-sequential ray tracing technique and fabricated using CNC machining.

2. DEVICE DESIGN

The design of the variable coupling ratio coupler is based on a simple Y-branch structure. The Y-branch structure is selected as it is the simplest optical splitting device which allows optical signal to be split symmetrically. A simple concept of attenuation caused by the lateral displacement of two fibers, as shown in Figure 3 is utilized for generating the non-symmetrical coupling ratios. The loss associated to this is given by the following relationship [13].

$$\alpha = -10 \log \left[1 - \frac{2SA_N}{3nd} \right], \tag{1}$$

where S is the separation between the two fibers, A_N is the numerical aperture of the fibers, n is the refractive index of the fibers and d is the diameter of the fibers.

Figure 4 shows a generic design structure for the proposed variable Y-branch POF coupler. The device consisted of a rectangular block with Y-branch structure engraved on it. POF fibers are slotted into

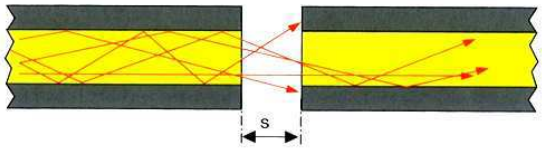


Figure 3. Attenuation induced by lateral displacement of two fibers [1].

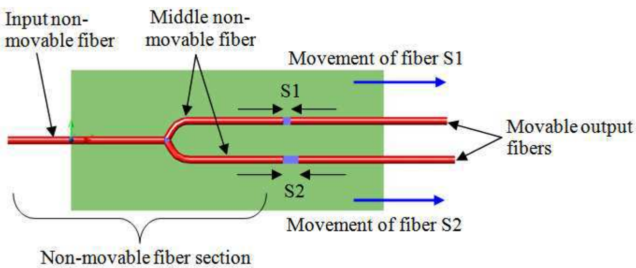


Figure 4. Generic Y-branch coupler with movable output fibers.

this structure and arranged accordingly as shown in the figure. The input fiber is a non-movable fiber. The output fibers, however are divided into two sections: non-movable and movable fibers. The fibers after the middle splitting junction are short non-movable fibers whereas the two outermost output fibers are defined as movable fibers.

Based on Figure 4, a relationship between the coupling ratios and the output fibers' lateral displacement (S_1 and S_2) can be obtained. Applying Equation (1), the attenuation at each output port of the device is given by α_1 and α_2 shown as follows.

$$\text{Output port 1:} \quad \alpha_1 = -10\log[1 - RS_1] \tag{2}$$

$$\text{Output port 2:} \quad \alpha_1 = -10\log[1 - RS_2] \tag{3}$$

where R is the value of $R = \frac{2A_N}{3nd}$ where the parameters A_N, n and d are defined earlier. Equations (2) and (3) are then applied to the optical power equation to give the following results.

$$P_1 = 10^{-(\alpha_1/10)} = 1 - RS_1$$
$$P_2 = 10^{-(\alpha_2/10)} = 1 - RS_2$$

where P_1, P_2 are the output powers at the two output port 1 and port 2 respectively. The results for P_1 and P_2 can be inserted into the coupling ratio Equation [6] of the form

$$CR = \frac{P_1}{P_1 + P_2}, \tag{4}$$

which will then give the following relationship,

$$CR = \frac{1 - RS_1}{2 - RS_1 - RS_2} \tag{5}$$

Equation (5) can be re-written into terms involving S_1 and S_2 giving,

$$S_1 = \frac{1}{R(1 - CR)} \left[1 - CR\,(2 - RS_2)\right], \tag{6}$$

Using the standard value of a step index (SI) POF fiber, where $A_N = 0.5$, $n = 1.49$ and $d = 1\,\text{mm}$, gives $R = 223.71$. The use of a symmetrical Y-branch coupler will ensure that the output power is divide equally by the waveguide taper in the middle. Figure 5 shows the design plot of the variable coupling ratio Y-branch coupler. The fiber optics lateral displacement on the x-axis is given in two separate displacements each for the S_1 and S_2. For a specific lateral displacement of S_2, a corresponding lateral displacement will be set for S_1. For example, when the output fiber at port 2 is moved by 0.1 mm, the corresponding fiber at port 1 will be moved by 4.4 mm. The lateral displacement of the output fibers varies from $S_1 = 4.4\,\text{mm}$ down to $S_1 = 1.6\,\text{mm}$ and $S_2 = 0.1\,\text{mm}$ to $S_2 = 1.0\,\text{mm}$. The equally split ratio value at 50% is obtained when the lateral displacements are equal, for example at $S_{1,2} = 0\,\text{mm}$. The coupling ratios (CR) obtained for this design vary from 1% to 45% for port 1 (CR1) and 99% down to 55% for port 2 (CR2).

The proposed structure for the variable POF coupler is based on Y-branch structure with a high-index contrast waveguide taper on

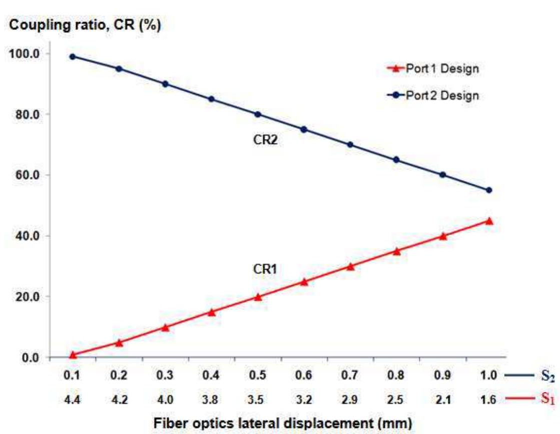


Figure 5. Coupling ratios against output fibers' lateral displacement: design.

acrylic or PMMA (*Poly(methyl methacrylate)*) material. The design of a symmetrical coupling ratio acrylic-based Y-branch coupler with high index contrast waveguide taper has been done and presented in reference [14]. Figure 6 shows the CAD (computer aided design) design layout of the new acrylic-based variable Y-branch POF coupler. The unique feature of this device is the middle suspended 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. 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. The U-grooves are designed with square cross sections which allow the 1 mm sized POF fibers to fit into these slots. Insert figure in Figure 6 shows a close view of the suspended waveguide taper structure.

The device structure in Figure 6 is composed of an input fiber, middle fibers, movable output fibers, device block that includes the high index contrast waveguide taper and open space region, and the top acrylic block. The input and middle fibers are non-movable fibers whereas the output fibers are movable fibers. The open space region in the form of a rectangular shaped void is placed after the middle non-movable fibers. The height of the open space region is 1 mm which allows the movement of the output fibers in the lateral displacement. This height will also ensure that the fibers are secured vertically and moved in the direction as required. The length of the open space region is about 5 mm.

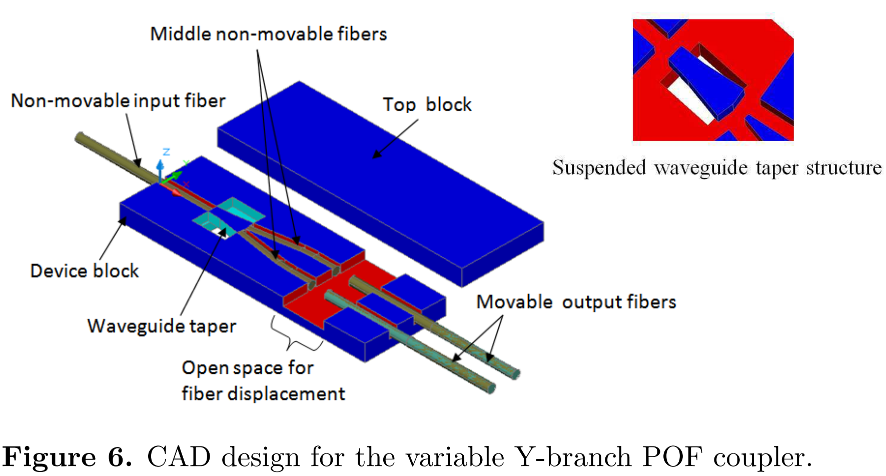


Figure 6. CAD design for the variable Y-branch POF coupler.

3. DEVICE SIMULATION

Due to the multimode characteristics of the POF coupler, ray-tracing technique has been used to analyze the optical performance of the device. The POF coupler is simulated using *non-sequential* ray tracing technique in *Zemax*. In the device simulation, the device and the top enclosing blocks are defined as PMMA material with the refractive index set at 1.49. The open space region and the space around the waveguide taper are open air and are not defined in the simulation. The fiber core is a cylindrical-shaped structure with a diameter of 980 μm shown in Figure 7(a). The cladding as shown in Figure 7(b) is also cylindrical-shaped structure but the inner part has been removed leaving only a thin cladding layer with an inner diameter equals to the core diameter of 980 μm and an outer diameter of 1000 μm. Figure 7(c) is the final structure of the fiber after both the core and cladding are combined. The refractive index for the fiber core is set at 1.49 and the cladding at 1.42. Figure 8 shows the 3D layout model of the variable POF coupler used for device simulation.

In the simulated model, the optical source is a rectangular source with a wavelength of 650 nm, and optical input power of 1.0 mW. When

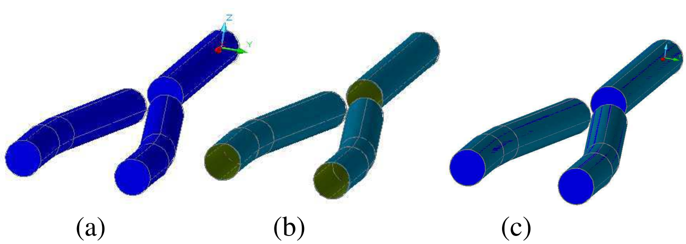


Figure 7. Design for POF fibers used in the simulation (a) core, (b) cladding, (c) both core and cladding are combined.

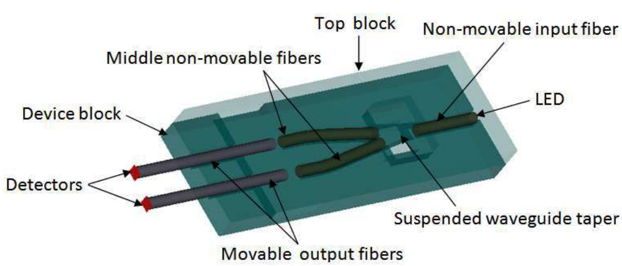


Figure 8. 3D model of the variable Y-branch POF coupler for device simulation.

the output fibers are not moved, the device operates as a 3 dB coupler with insertion losses of 4.92 dB and 4.79 dB. The excess loss is about 1.84 dB with a coupling ratio of almost 50 : 50. Figure 9(a) and Figure 9(b) are the 2D ray tracing results for the device when the output fibers are not shifted and when the output fibers are shifted respectively. When the output fibers are not moved, the device has insertion losses of 4.81 dB and 4.88 dB. The excess loss is about 1.83 dB with a coupling ratio of almost 50 : 50. This shows that the Y-branch coupler works as a 3 dB coupler.

Figure 10 shows the plot of the coupling ratios against the output fibers' lateral displacement. The plotted coupling ratio was obtained by using the coupling ratio equation given by Equation (4). The coupling ratio vary from 7.65% to 39.85% for port 1 (CR1) and from 92.35% down to 60.15% for port 2 (CR2). As a comparison, the coupling ratios for the design are also included.

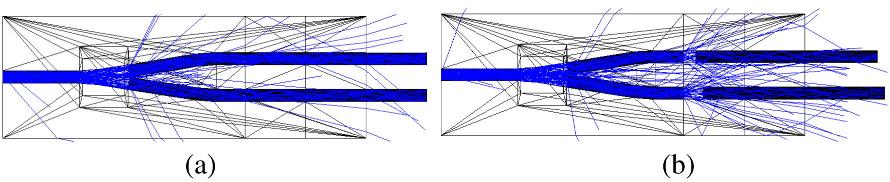


Figure 9. 2D ray tracing layout of acrylic-based Y-branch POF coupler (a) non-shifted output fibers, (b) shifted output fibers.

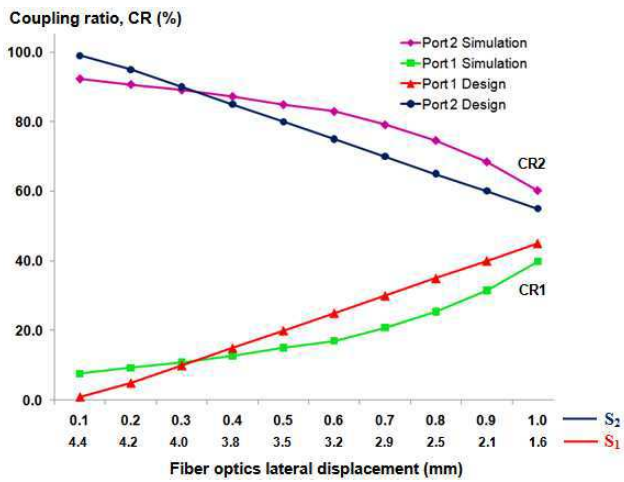


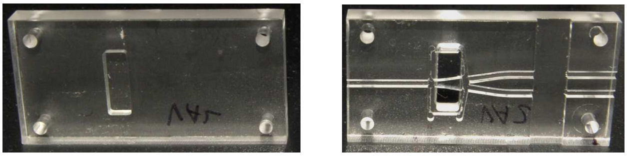
Figure 10. Coupling ratios against output fibers' lateral displacement: simulated devices.

4. FABRICATION AND CHARACTERIZATION

The fabrication of the variable Y-branch POF coupler is done using a simple and low cost technique. The designed structures are engraved onto acrylic block using Roland's EGX-400 desktop CNC machine at a spindle speed of 15,000 rpm. The milling tool used is a 2-flute, 30° *Helix* shape, 1.0 mm diameter endmill tool. In addition to the engraved design structure, 4 holes are drilled at each corner to allow a top enclosing block to be screwed on top and enclosed the device structure.

Due to the machining requirements, a lubrication system was installed to this engraver. The lubrication system used is oil based. The lubricant is injected using a small nozzle onto the device block during the machining process. The main function of the lubricant is to lower down the temperature of the material due to the high speed machining process and enables the surface finishing of the engraved structures to be much smoother and less rough.

Figure 11(a) shows the fabricated top enclosing block while Figure 11(b) is the fabricated device block. These fabricated acrylic blocks have been carefully engraved to ensure the engraved U-groove slots are within the right dimensions, in particular the height of the waveguide taper which must be within 1 mm. These two block are then sandwiched together and secured using screws. After the device structure has been engraved, short unjacketed SI POF fibers comprising the components for the input and middle non movable fibers are inserted into the engraved slots until they are aligned to the waveguide taper. Figure 12 provides a close view of the suspended waveguide taper structure. The figure shows how the input and middle nonmovable fibers are butt-coupled and passively aligned to the waveguide taper. Figure 13(a) shows how the POF fibers are inserted and positioned into the U-groove slots of the device block. Figure 13(b) is the assembled device with the top block enclosing the whole device structure.



(a) (b)

Figure 11. Fabricated components (a) top enclosing block, (b) device block.

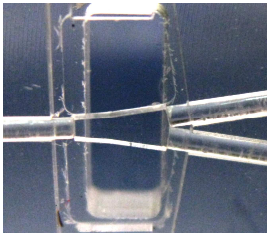
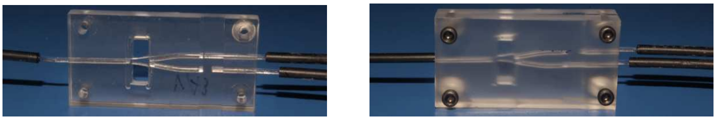


Figure 12. Close view of the suspended waveguide taper structure with fibers inserted and aligned.



(a) (b)

Figure 13. Assembled variable Y-branch POF coupler (a) device block with fibers inserted and aligned, (b) enclosed device.

The insertion loss of this device has been tested at a wavelength 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 when both the movable output fibers are not shifted is 8.3 dB and 9.5 dB respectively with an excess loss of 5.85 dB while the coupling ratios are at 56.86% and 43.14%. The output fibers are moved laterally using a single-axis miniature translation stage with a 250 μm displacement per revolution. Figure 14 shows the setup for the POF coupling system with the miniature translation stage connection.

Figure 15 is the plot of the coupling ratios against the output fibers' lateral displacement for the fabricated device. The coupling ratio was obtained by using Equation (4). As a comparison, both the coupling ratios for design and simulated devices are also included. The fabricated device shows coupling ratios variation from 10.09% to 32.88% for port 1 and 89.91% down to 67.12% for port 2. The excess loss of this device varies from 5.85 dB to 8.49 dB. The results showed that the Y-branch coupler works as a variable coupler. It showed that the integration of the suspended high index contrast waveguide taper and the fiber attenuation technique can produce a low cost variable coupler with a large range of non-symmetrical coupling ratios. The work here also proved that a simple Y-branch coupler can be simply

(a) (b) (c)

Figure 14. Setup for POF system coupling (a) optical source and mode scrambler, (b) deviceunder-test and two miniature translation stages, (c) power meters.

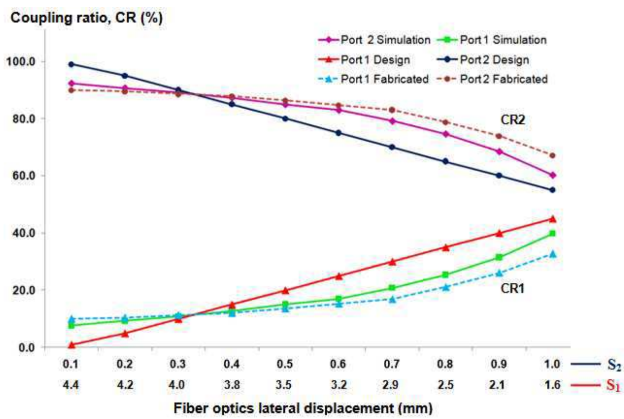


Figure 15. Coupling ratios against output fiber lateral displacement: fabricated devices.

converted from working as a 3 dB coupler to a multi-coupling ratio optical device which not only function as a variable coupler but it also works theoretically as an asymmetric coupler when only one output fiber is laterally displaced.

The fabricated device has higher excess loss compare to that of the model device. One of the major loss contribution is the coupling loss between the fibers and the waveguide taper, and between the middle non-movable fibers and the movable output fibers. Geometrical coupling errors between the fibers and the waveguide taper is one of the factor that contribute the loss. The fibers are basically circular in shape whereas the coupled-end of the waveguide taper is square in shape. This geometrical structure mismatch caused some light rays to disperse out of the waveguide taper and not propagating into the coupled fibers. The waveguide taper has a large NA due to the large index difference between the PMMA-based waveguide taper and air cladding surrounding this structure. This causes a large NA mismatched between the fibers and waveguide taper and hence contribute to the coupling loss.

In addition, scattering due to the surface roughness of the waveguide taper also contribute to the loss. 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. The low-grade and low-purity acrylic materials used are also major contributions to the high loss. In this project, we used low-cost acrylics which are mainly used in decoration for souvenirs or as casing in all sort of applications. The coupling loss of this device can be improved by introducing an index matching gel between the POF fibers and the waveguide taper, and using high-grade PMMA materials.

5. CONCLUSION

We have successfully developed an acrylic-based variable Y-branch POF coupler. The device which utilizes a Y-branch structure provides much simpler and compact device design. It avoids the used of bulky external attenuators attached to a symmetrical Y-branch coupler. The proposed simple attenuation technique caused by the lateral displacement of two fibers has been proven to provide the required non-symmetrical coupling ratios and allowed a much simpler control for the variable coupler. The device manufactured using CNC machine has given a range of coupling ratios from 10.09% up to 89.91%. In addition to the variable coupler, the same design can also be utilized for an asymmetric Y-branch coupler where instead of shifting two fibers, only fiber is laterally displaced while the other fiber is stationary. This unique Y-branch design together with the attenuation technique caused by lateral displacement of two fibers would enable this device to work in multi-function mode: 3 dB, asymmetric and variable coupling ratio modes. Finally, this acrylic-based coupler is simple to fabricate and low-cost plastic injection molding can be utilized for future mass-production.

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