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Asymmetric Y-branch plastic optical fiber coupler

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An acrylic-based asymmetric Y-branch plastic optical fiber (POF) coupler has been developed. The optical device is based on a Y-branch coupler design with a middle high index contrast waveguide taper and open space region for output fiber displacement. The middle waveguide taper is constructed on the acrylic block itself without using any additional optical waveguiding medium injected into the engraved taper region. The waveguide taper allows light rays to propagate by total internal reflection and this is achieved by having the material surrounding the waveguide taper to be of a lower refractive index (RI) than that of acrylic (RI of acrylic is 1.49). The area surrounding the waveguide taper has been designed in such a way that it is surrounded by an open air with an RI of 1.0. The high index contrast structure enables large splitting angle and shorter device length. Input and output POFs are inserted into this device structure in such a way that they are passively aligned to the middle waveguide taper structure. A simple attenuation technique based on lateral displacement of two fibers has been proposed and presented for the non-symmetrical coupling ratios. Numerical analysis has been made on the lateral displacement of the output fibers which shows that the device is able to generate non-symmetrical coupling ratios. A simple relationship between the coupling ratios and output fiber separation has been obtained. Device modeling has been performed using non-sequential ray tracing technique on the Y-branch coupler performing as a simple 3 dB coupler with excess loss of 1.83 dB and a coupling ratio of 50:50. The non-symmetrical coupling ratios of the device have been simulated by varying the lateral displacement of one output fiber from 0.1 mm to 4.4 mm. The results for the coupling ratios against the fiber displacement have been obtained and show how the device can be operated as an asymmetric Y-branch POF coupler.

Keywords: acrylic, asymmetric, coupler, plastic optical fiber (POF), waveguide taper, Y-branch.

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 vaster 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 type POF couplers are of great importance in these applications for the splitting and coupling of light signals. One of the simplest types of an optical splitting device is the Y-branch coupler. Fiber-based Y-branch POF couplers are normally constructed by polishing two fibers and gluing them together. Even though their production cost is low, the non-symmetrical ratio couplers are difficult to produce as they require different polishing level and accuracy. As for the planar type couplers, several types of symmetrical ratio Y-branch couplers have been reported. MIZUNO *et al.* [2], KLOTZBUECHER *et al.* [3] and TAKEZAWA *et al.* [4] have all reported on planar waveguide based symmetrical Y-branch POF couplers with large core sizes (1000 μm).

In addition to the symmetrical ratio couplers, there have been reported several designs of the planar waveguide based Y-branch coupler with asymmetric coupling ratios. The first is the device reported by SUZUKI *et al.* [5] which is a single-mode Y-branch coupler with the center axis of the branching output waveguide and the center axis of the taper waveguide shifted from each other. The second asymmetric coupler design is a multimode Y-branch waveguide device reported by KUROKAWA *et al.* [6]. In this Y-branch waveguide design, advantage is taken of the reflection at the reflecting surface of the waveguide to divide the optical power, independent of the branch corner [6]. Another asymmetric coupler which has been proposed by LIN *et al.* [7] is a single-mode Y-branch coupler using microprisms. The power-splitting ratio is controlled by varying the lengths of prisms for both fixed branching angle and prism index [7]. Another version of the asymmetric waveguide coupler has been reported by HENRY and LOVE [8]. The asymmetric multimode Y-junction splitter is wavelength independent and has non-reciprocal splitting properties. The power splitting ratio is controlled by the geometry size of the output branch. In addition, we have also developed our own asymmetric POF coupler based on metal-hollow structure. The design has been simulated and fabricated on aluminum substrate and shows coupling ratios from 10.7% to 47.7% [9, 10].

In this paper, we proposed an asymmetric coupler design based on a simple Y-branch structure. This Y-branch design is constructed using low-cost acrylic material. The non-symmetrical coupling ratios are obtained by using a simple theory of attenuation caused by the lateral displacement of two fibers. The asymmetric coupler design is modeled using non-sequential ray tracing technique. The theoretical design is then compared with the ray tracing results.

2. Device design

The design of the asymmetric coupler is based on a simple Y-branch structure. The Y-branch structure is selected as it is the simplest optical splitting device which

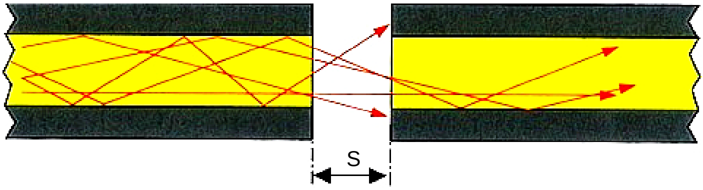

Fig. 1. Attenuation induced by lateral displacement of two fibers [1].

allows optical signal to be split into two ones symmetrically. The non-symmetrical coupling ratio is obtained using this structure taking advantage of a simple concept of attenuation caused by the lateral displacement of two fibers. The following shows some of the theoretical works.

The theory behind the non-symmetrical coupling or splitting lies in the following principle. The attenuation caused by the lateral displacement of two fibers is shown in Fig. 1.

The loss associated to it is given by the following relationship [11]:

$$\alpha = -10\log\left(1 - \frac{2SA_N}{3nd}\right) \tag{1}$$

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.

The analysis for the coupling ratios of the Y-branch coupler using the attenuation induced by lateral displacement of two fibers is shown as follows. The analysis will utilize a simple generic Y-branch device shown in Fig. 2**a**. The device in Fig. 2**a** basically consists of a block with a Y-branch structure engraved on it. POFs are then slotted into this structure and arranged accordingly as shown in the figure. The input fiber is a non-movable one. 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. Another section of the output fibers are defined as movable. Figure 2**b** shows the lateral movement of the output fibers giving an example of lateral displacement of S_1 and S_2. In the asymmetric Y-branch coupler design, only one output fiber is made movable while the other output fiber remains stationary.

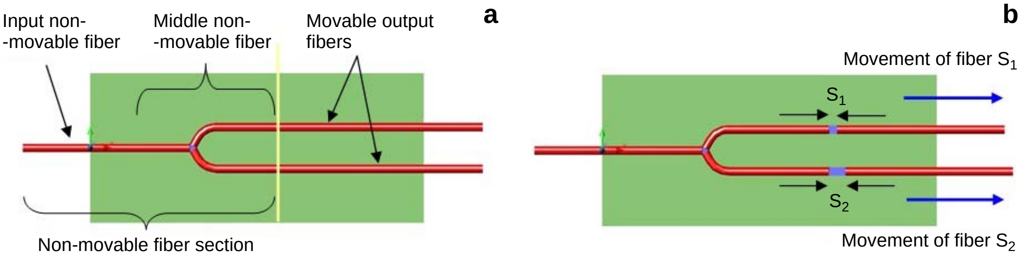

Fig. 2. Generic Y-branch coupler with movable output fibers, showing lateral displacement of S_1 (**a**) and S_2 (**b**).

If we assume that at $S_{1,\,2} = 0$, the device has an insertion loss of α. As the fibers are separated by a distance S_M the attenuation of the device will be

$$\alpha_M = -10\log\left(1 - \frac{2S_M A_N}{3nd}\right) \tag{2}$$

The attenuation of each port of the device is given by α_1 and α_2 as follows,

$$\text{Output port 1: } \alpha_1 = -10\log\left(1 - RS_1\right) \tag{3}$$

$$\text{Output port 2: } \alpha_2 = -10\log\left(1 - RS_2\right) \tag{4}$$

where R is the value of $R = 2A_N/3nd$, with the parameters A_N, n and d being defined earlier. Using a simple optical power (attenuation) equation and both Eqs. (3) and (4) gives the following results

$$P_1 = 10^{-\frac{\alpha_1}{10}} = 10^{\frac{10\log(1-RS_1)}{10}} = 10^{\log(1-RS_1)} = 1 - RS_1$$

$$P_2 = 10^{-\frac{\alpha_2}{10}} = 10^{\frac{10\log(1-RS_2)}{10}} = 10^{\log(1-RS_2)} = 1 - RS_2$$

where P_1 and P_2 are the output powers at the two output ports of the device.

The coupling ratio CR is given by the following relationship [5]

$$\mathrm{CR} = \frac{P_1}{P_1 + P_2} \tag{5}$$

The results for P_1 and P_2 and Eq. (5) are then used in order to get a relationship between the coupling ratio and the lateral displacement

$$\mathrm{CR} = \frac{P_1}{P_1 + P_2} = \frac{1 - RS_1}{1 - RS_1 + 1 - RS_2} = \frac{1 - RS_1}{2 - RS_1 - RS_2} \tag{6}$$

Rearangging the above equation gives the following relationship of the fiber displacement S_1 as a function of the fiber displacement S_2 and the coupling ratio

$$S_1 = \frac{1}{R(1 - \mathrm{CR})}\left[1 - \mathrm{CR}(2 - RS_2)\right] \tag{7}$$

In the analysis, we assume that only one output fiber is moved whereas the second output fiber remains unmoved. Therefore, we can simplify Eq. (7) into the terms

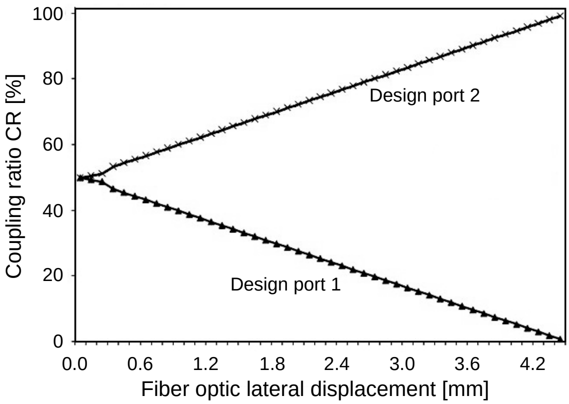

Fig. 3. Coupling ratio against output fiber lateral displacement for asymmetric Y-branch POF coupler.

involving the coupling ratio and fiber displacement S_1 only ($S_2 = 0$), shown as follows,

$$\text{CR} = \frac{1 - RS_1}{2 - RS_1} \tag{8}$$

Using the standard value of a step index POF, where $A_N = 0.5$, $n = 1.49$ and $d = 1$ mm, gives $R = 223.71$. The use of a symmetrical Y-branch coupler will ensure that the output power is divided equally by the waveguide taper in the middle. This means that, for an input power of 1 mW, both outputs will have 0.5 mW when the fiber is at 0 position, or $S_{1,\,2} = 0$ mm. By using Eq. (8), the value of P_1 can be obtained by assuming an input power of 1 mW, $P_2 = 0.5$ mW and lateral displacement of the output fiber S_1 varies from 0.1 mm to 4.4 mm.

Figure 3 shows the design plot of the non-symmetrical Y-branch POF coupler. The plotted coupling ratio was obtained by using Eq. (7) with $S_2 = 0$ and the lateral displacement of the output fiber S_1 varying from 0.1 mm to 4.4 mm. The coupling ratio varies from 0.8% to 99.2%.

3. Device modeling and analysis

Due to the multimode characteristics of the POF coupler, ray-tracing technique has been used to model these optical devices. The modeling of the POF couplers is done using non-sequential ray tracing in Zemax.

The structure proposed for the asymmetric Y-branch POF coupler is constructed based on acrylic or PMMA (poly(methyl methacrylate)) material. The design will be based on Y-branch structure with a high-index contrast waveguide taper. The design of the symmetrical acrylic-based Y-branch coupler with high index contrast waveguide taper has been done and presented in Reference [12]. Figure 4 shows the CAD design layout of the new acrylic-based asymmetric Y-branch POF coupler showing the indi-

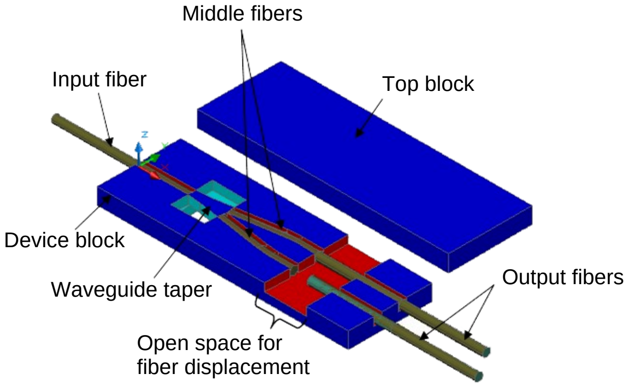

Fig. 4. CAD design for acrylic-based asymmetric Y-branch POF coupler.

vidual components for the device construction. The unique feature of this device is the middle acrylic waveguide taper with its refractive index (RI), n_{co} of 1.49 and surrounded by an open air cladding with RI, 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 POFs 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 POFs to fit into these slots.

The device structure in Fig. 4 is composed of an input fiber, middle fibers, output fibers, device block which includes the middle 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. In this asymmetric coupler mode, only one of the output fibers is movable whereas the other fiber remains stationary. The open space region in the form of a rectangular shape block 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 secure vertically and move in the direction as required. The lateral distance of the open space region is about 5 mm.

In order to perform the non-sequential ray tracing of the device, the device structure is divided into five component blocks. These components are shown in Fig. 5 which is a 3D layout model for the simulation tool. These are the device block, the top block, input and middle fibers, and movable output fibers. All fibers are composed 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. The bottom 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.

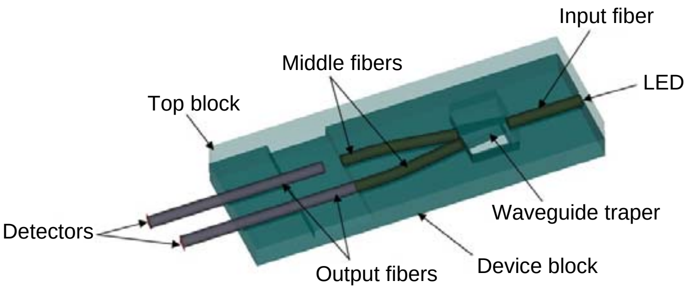

Fig. 5. 3D model of the acrylic-based asymmetric Y-branch POF coupler for device simulation.

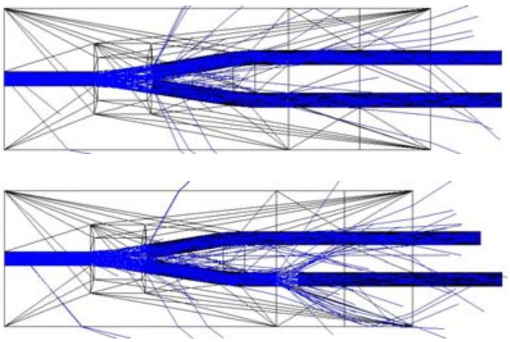

Fig. 6. 2D ray tracing layout of acrylic-based asymmetric Y-branch POF coupler: fibers non-displaced (**a**), and shifted output fiber (**b**).

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 POF cladding thickness. The refractive index for the fiber core is defined as 1.49 and the cladding as 1.40. Both the core and the cladding when combined will represent the step index (SI) POF.

The ray tracing of the devices has been performed using Zemax non-sequential ray tracing tool. In this model, the optical source is from a rectangular source with a wavelength of 650 nm, and optical input power of 1.0 mW. Figures 6**a** and 6**b** are the 2D ray tracing results for the device when the fibers are not shifted and one of the output fibers is shifted, respectively. Similarly, Figs. 7**a** and 7**b** are the 3D shaded ray tracing results for the device. 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.

The 2D ray tracing layout in Fig. 6 shows some scattering light rays at the waveguide taper. Figure 7 which is the 3D ray tracing layout shows a much better view of

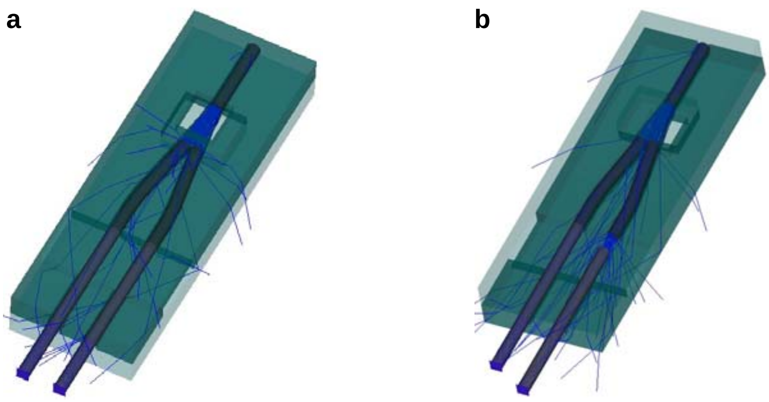

Fig. 7. 3D ray tracing layout of acrylic-based asymmetric Y-branch POF coupler: fibers non-displaced (**a**), and shifted output fiber (**b**).

how these rays are scattered out of the waveguide taper region at the coupling end between the taper and the middle fibers. The scattering is due to two major factors: *i*) geometrical coupling errors between the fibers and the waveguide taper, *ii*) non-matching of numerical apertures (NA). 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 basically 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 mismatch between the fibers and waveguide taper and hence contribute to the coupling loss.

Light ray scattering in the open space region is also observed. When the two fibers in this region are separated from each other, light rays coming out of the middle fiber are scattered. The degree of scattering depends on the fiber separation. The larger the separation is, the more light rays will be scattered and cause the high attenuation loss, as given by the fiber attenuation in Eq. (1).

In order to obtain the results for the non-symmetrical coupling ratios, one of the output fibers is displaced or shifted at a predetermined space. Here, the displacement is defined in the design where it varies from 0.1 mm to 4.4 mm, with a 0.1 mm step. The other output fiber remains stationary, as shown in Figs. 6**b** and 7**b**. The results are shown in Fig. 8 as plots of the coupling ratios against the output fiber lateral displacement. Port 1 and port 2 refer to the movable output fiber and non-movable output fiber, respectively. The coupling ratios for the plots are calculated using Eq. (6) based on the simulated output power obtained from the simulator tool. In addition, in this plot, the coupling ratios for the simulated device are compared with the design values. Both plots show some similarity in which the coupling ratios vary with the fiber separation but the variation of coupling ratios for the simulated device

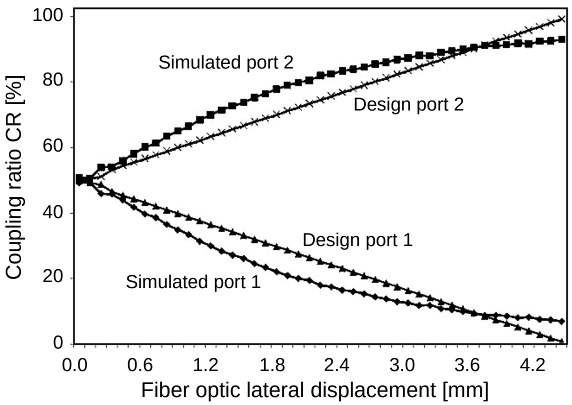

Fig. 8. Coupling ratio against output fiber lateral displacement for asymmetric Y-branch POF coupler.

deviates from a linear variation compared to that of the designed one. In the design, assumption has been made where the relationship between the coupling ratios and fiber separation is consistent throughout the displacement range. In the simulated model, the real device parameters are used which include the effect of coupling loss, material absorption and the semi-closed geometrical structure of the open space region where the fibers are separated. Due to light rays absorption in the acrylic and those being bounced off the surface of the acrylic, as the fiber separation gets larger, the geometrical coupling errors between the output fiber will increase. This geometrical mismatch caused some light rays to disperse out of the middle outgoing fiber and not propagating into the coupled output fiber.

4. Conclusions

In this paper, we have successfully presented the design and ray tracing modeling of an asymmetric Y-branch POF coupler. The device design is based on acrylic material and a middle high index contrast waveguide taper constructed on the acrylic block itself without using any additional optical waveguiding medium. It has been shown that the waveguide taper allows lights rays to propagate by total internal reflection and this is achieved by having the material surrounding the waveguide taper to have a lower refractive index than that of acrylic. A simple attenuation technique caused by the lateral displacement of two fibers has been proposed and presented for the non--symmetrical coupling ratios. Modeling has been performed using non-sequential ray tracing technique and shows the Y-branch coupler performed as a simple 3 dB coupler with an excess loss of 1.83 dB and a coupling ratio of 50:50. The non-symmetrical coupling ratio of the device has been simulated by varying the lateral displacement of one output fiber from 0.1 mm to 4.4 mm. The results for the coupling ratios against the fiber displacement have been obtained and show how the device can be operated as an asymmetric Y-branch POF coupler. This work is part of our work on developing a low cost acrylic-based asymmetric and variable coupling ratios POF coupler. The second part of this work will be to fabricate this device structure on an acrylic block using high speed CNC machining tool.

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