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Three-Step Molding Softlithographic Process for 1×2 Y-Branch POF Coupler

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Abstract—A three-step molding softlithographic process has been developed for the construction of a sharp Y-junction structure formation in a 1×2 Y-branch plastic optical fiber (POF) coupler design. The 1×2 Y-branch POF coupler is based on a Y-junction splitter which requires that the splitting part is constructed with sharp infinitesimal junction. The softlithographic process enables a PDMS mold to be constructed which then allows mass replication of the polymer-based POF coupler. A standard master mold based on PMMA material is fabricated using CNC milling. A secondary or auxiliary-mold process step is then introduced in order to produce a sharp Y-junction structure which is then transferred to the final PDMS stamp prior to device replication. This step utilizes a free flowing, low viscosity casting-based resin, which after curing and hardening provide the auxiliary mold for PDMS mold fabrication. The result shows that a very fine and sharp Y-junction structure can be produced easily which cannot be produced via standard two step molding softlithographic process. Models for the Y-branch POF coupler produced with and without an auxiliary mold process are constructed which show that a 16% increased in optical performance with the device replicated with the auxiliary mold process.

1. INTRODUCTION

Plastic Optical Fiber (POF) is a widely recognized optical medium for short distance optical data communication due to its favorably large-core size, multimode characteristics, low cost and robust features. Many applications for multimode fibers are well known. Nevertheless, waveguide-based POF devices development is limited because multimode devices have a smaller market especially for data communication application due to the high attenuation of POF devices compared to that of glass-based optical devices [1].

POF devices are produced with variety of new and economical materials for vast application which not only are for optical communications, but also include the entertainment, sensor, lighting and decoration system fields [2]. POF devices can be categorized in two parts: active and passive components. Active component are devices such as transmitter and receiver whereas passive component are devices such as filters, connectors, attenuators, and coupler or splitter, and other related passive devices [3]. Coupler or splitter as a passive device has great interest in applications in such as short length networks, optical sensors, and security system. These applications sometimes require that optical signals need to be split or divided.

Standard fiber-based Y-branch couplers are normally made by polishing two fibers and gluing them together. These Y-branch couplers are vastly used in applications where incoming light signals need to be split. Nevertheless, this technique will be very impractical for producing asymmetrical-type couplers

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as these devices require different polishing level and accuracy. Large symmetrical waveguide-based Y-branch POF couplers with core sizes (1000 µm) have been previously described by Takezawa et al. [4], Mizuno et al. [5]), and Klotzbuecher et al. [6]. Mizuno et al. developed a Y-branch device based on hot embossing technique where a rigid mold and UV-curable epoxy resin for the core material are utilized. Another fabrication technique based on laser-LIGA and micro-injection technique has been utilized by Klotzbuecher et al. Mold insert was produced using laser ablation technique Photo-curable resin was injected into the waveguide channel using a small syringe. The above mentioned fabrication techniques for Y-branch coupler, unfortunately require expensive production equipment and precision assembly tools.

In order to overcome this problem and obtaining a high throughput, a softlithographic replication process has been proposed. Softlithography is a replication technique that requires the use of a polydimethylsiloxane (PDMS) rubber stamp which normally will be fabricated using a master mold. In this paper, we report the fabrication of large core polymer-based 1×2 Y-branch POF coupler using a three-step molding softlithographic process. The Y-branch POF coupler design requires a sharp splitting or a Y-junction structure in order to obtain low insertion loss. The master mold of the Y-branch device is designed and then fabricated using CNC milling. A secondary or auxiliary mold step is introduced prior to transferring the master mold pattern onto the PDMS rubber mold. This auxiliary mold will allow a sharp Y-junction structure to be constructed when the pattern is transferred to the PDMS rubber mold. Using this final PDMS mold, optically clear material can then be transferred onto a lower refractive index substrate which functions as the cladding region. The core of the proposed optical device is based on an optically clear epoxy resin Epotek OG142 material whereas the cladding is based on PMMA or acrylic material.

2. DEVICE DESIGN

The design of a polymeric 1×2 Y-branch POF coupler is presented. In this design, both the input and output waveguide widths have the same cross section width. The design is based on a simple 1×2 Y-junction coupler where the input optical power is split into two or 50:50 coupling ratio. Figure 1 shows the two dimension (2D) layout of the Y-branch coupler design. The design is based on the previous design by the authors on the Y-branch coupler device developed based on a high index contrast waveguide taper design [7]. The device is designed with design parameters as follows: length is set at 20 mm, waveguide width is 1 mm which is compatible with a 1 mm step index (SI) POF fiber, branching radius is 10 mm, and the splitting angle is set at 18°. As shown in Figure 1, the junction is a sharp Y-junction structure.

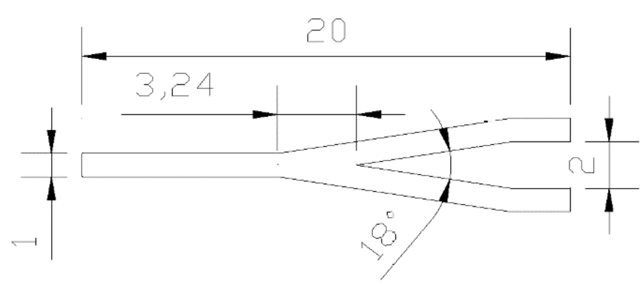


Figure 1. 1×2 Y-branch device design structure.

In the construction of the Y-branch device, an analysis on the geometrical feature of the device has to be considered in order to obtain optimum waveguide taper length, d. In [8], Beltrami has provided a comprehensive analysis on the optimum taper length in a two refractive-index system for a Y-junction multimode waveguide. Based on the work provided by Beltrami [8] and Ehsan et al. [7, 9], the parameters for the minimum taper length and splitting angle were obtained. In this Y-branch design, the refractive indices are set at 1.58 for the waveguide core, n_{co} which is the value for the optical polymer OG142 and the cladding index, n_{clad} is set at 1.49 which the value of that of a PMMA material. The optical polymer OG142, which has a refractive index of 1.58, allows light transmissions at 97%.

3. DEVICE SIMULATION

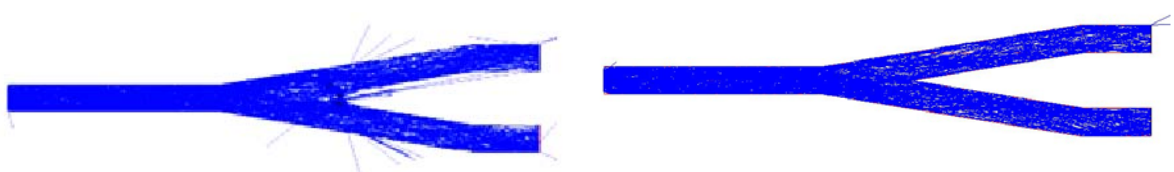
The 1×2 Y-branch coupler device is simulated using a non-sequential ray-tracing simulation tool, *Zemax*. In the ray tracing modeling, the optical source is from a rectangular source with a wavelength of 650 nm, and with an input power of 1.0 mW. The core of the waveguide is based on a UV curable epoxy resin, Epotek OG142 with an index of refraction of 1.58. The cladding for the waveguide is PMMA material with an index refraction of 1.49.

Two sets of designs are used for modeling of the devices. These two designs will enable the optical properties of the device based on the geometrical structure at the Y-junction to be evaluated. The first design will have a circular curvature which has the same diameter as the actual tool diameter used in the CNC milling of the master mold, about 0.5 mm. The second design will have a sharp Y-junction structure. These two sets of designs are shown in Figure 2. The device modeling on these two design structures will enable the optical properties for both devices to be obtained and compared.

(a) (b)

Figure 2. 2D layout of device. (a) Design 1 (radius at Y-junction). (b) Design 2 (sharp Y-junction).

Figure 3 shows the 2D ray tracing results for the proposed designs. Figure 3(a) shows that at the Y-junction, some scattered rays can be seen due to the small circular curvature caused by the tooling radius. In contrast, there are no scattered rays at the Y-junction of the device with the sharp Y-junction as shown in Figure 3(b). The output power obtained for design 1 are 0.402 mW at port 1 and 0.390 mW for port 2 respectively. Similarly, output power obtained for design 2 are 0.489 mW at port 1 and 0.487 mW for port 2, respectively.



(a) (b)

Figure 3. 2D ray tracing diagram for 1×2 Y-branch POF coupler. (a) Design 1. (b) Design 2.

The coupling ratio (CR) of the device, can be obtained using the following equation [10]:

$$\mathrm{CR} = \frac{P_1}{P_1 + P_2} \tag{1}$$

where P_1 and P_2 are the output power (in mW) at the two output ports of the Y-branch. The excess loss can be calculated based on the following relationship [4]:

$$\alpha = -10 \log \left(\frac{P_1 + P_2}{P_{in}} \right) \tag{2}$$

where P_1 and P_2 are the powers at the two outputs while P_{in} is the input power.

The values for the coupling ratios and excess loss for design 1 and design 2 are CR $= 51 : 59$, $\alpha = 1$ dB and CR 50:50, $\alpha = 0.1$ dB respectively.

4. FABRICATION AND CHARACTERIZATION

The 1 × 2 Y-branch POF coupler will be developed using a simple replication method known as softlithography. Softlithography is a valuable replication technique normally used for replicating microfluidics devices. Softlithography involves a soft polymeric mold component such as a PDMS which is replicated from an original rigid master mold. Master molds are normally fabricated by photolithographic process in order to define a PDMS stamp pattern [11]. These PDMS stamps can then be used to replicate the devices. Figure 4 illustrates the common process of producing the polymeric waveguide coupler from a PDMS stamp. The waveguide fabrication process involves injecting the UV curable polymer resin into the engraved patterned or cavities on the PDMS stamp with a bottom substrate material in placed. The resin is then UV cured and the PDMS mold is then peeled off from the bottom substrate.

The fabrication process of the coupler will involve two separate softlithographic processes. The two sets of processes will demonstrate how a simple auxiliary molding step will enable a sharp Y-junction structure to be produced. The first process will involve a standard two-step molding process whereas in the second process involve a three-step molding process. Two sets of master molds will be produced to illustrate how the final shape of the Y-junction will be formed. The first master mold design will have the material protruding outside or extend beyond and above the material surface. This is shown in Figure 5(a). The second design, however will have a master mold with the Y-shape structure engraved into the master mold material as shown in Figure 5(b).

The master mold is fabricated using a simple computer numerical control (CNC) milling machine. The material used for the master mold is PMMA. The diameter of the endmill tool used is 0.5 mm, and

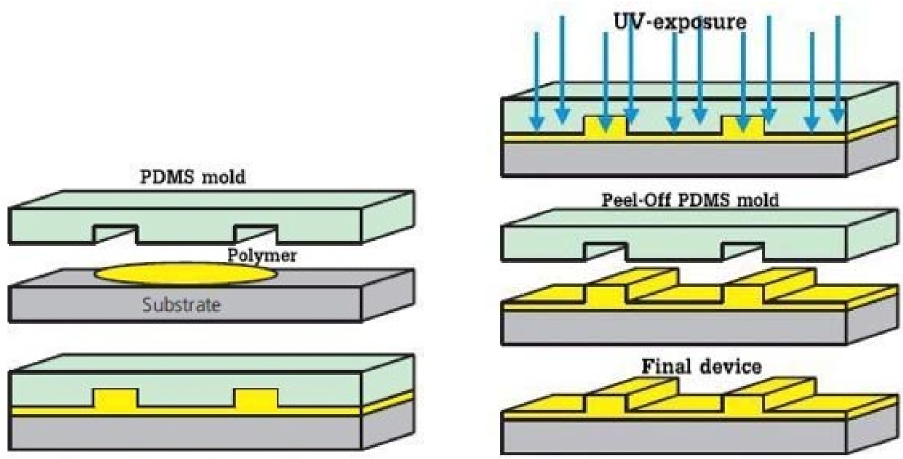


Figure 4. Fabrication steps for producing waveguide coupler device from PDMS mold.

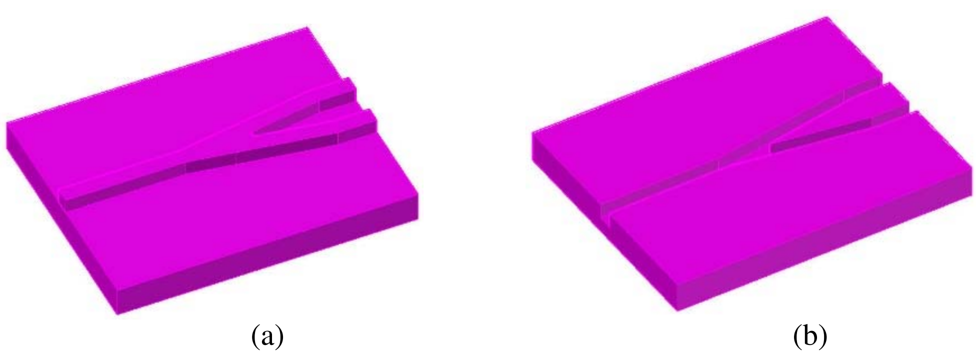


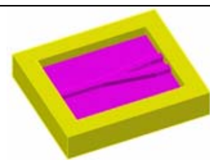
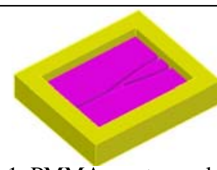
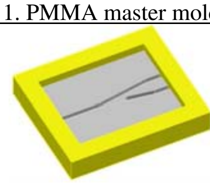
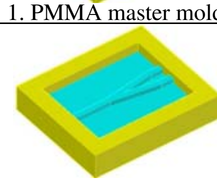
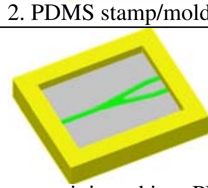
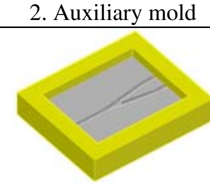
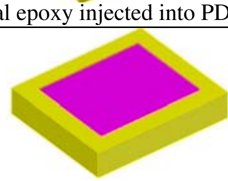
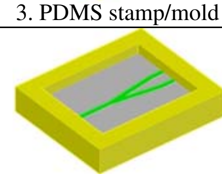
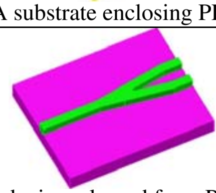
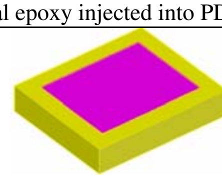
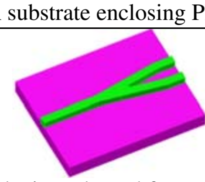
Figure 5. Master mold designs. (a) Design 1 (protrude). (b) Design 2 (engraved).

the machine spindle speed is 15,000 rpm. Design 1 has been fabricated in which a PDMS stamp will be replicated directly from the master mold. However, for the second design where the Y-shape structure on the master mold is engraved instead of being protruded, an additional simple step will be taken. This additional step will utilize a casting type process where an auxiliary mold will be introduced in the softlithographic process flow. This step will ensure that the final PDMS stamp will have the same geometrical feature as that of the master mold which has an engraved surface of the Y-shape structure.

The material used for the three-step molding process is a casting material, Epokwick from Buehler. Epokwick is a medium viscosity, transparent, and fast curing epoxy which can produce hard mounts with good edge retention characteristics. In the first design, which involve a two-step molding process, the final PDMS stamp will be used to replicate the polymeric optical device. Comparably, in the second design, which involve a three-step molding process, the PDMS stamp replicated from the auxiliary mold will be used to replicate the polymeric optical device.

The fabrication of the polymeric coupler is done using an optical epoxy resin, Epotek OG142. The epoxy has been selected due to its optical properties and a mid-value viscosity of 9,000 cps which can

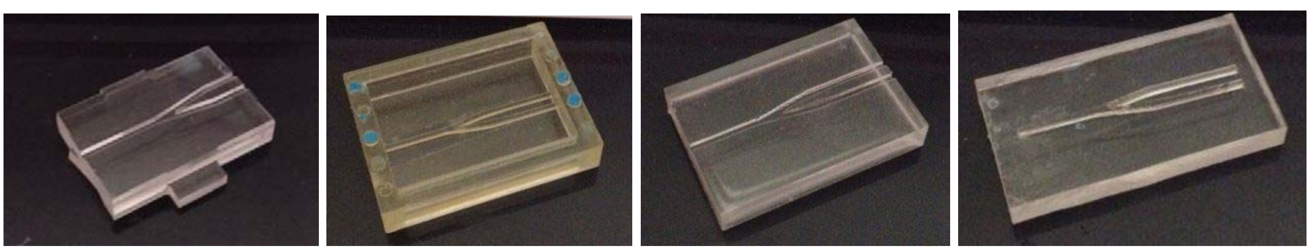
Table 1. Comparisons of process flow for optical device fabrication.

Two-step molding process (Design 1)	**Three-step molding process (Design 2)**
 1. PMMA master mold	 1. PMMA master mold
 2. PDMS stamp/mold	 2. Auxiliary mold
 3. Optical epoxy injected into PDMS mold	 3. PDMS stamp/mold
 4. PMMA substrate enclosing PDMS mold	 4. Optical epoxy injected into PDMS mold
 5. Optical device released from PDMS mold	 5. PMMA substrate enclosing PDMS mold
	 6. Optical device released from PDMS mold

be easily poured into the PDMS mold cavity. In general, the device fabrication process will involve pouring the epoxy into the PDMS mold until the liquid resin fill up the cavities of the Y-junction. A second PMMA material which has a lower refractive index than that of OG142 is pressed on top of the PDMS mold. The PMMA substrate will act as the substrate for the 1×2 Y-branch POF coupler. The epoxy Epotek OG142 is then cured using UV light source at 365 nm wavelength. The intensity of the UV light source is set at $100\,\mathrm{mW/cm^2}$, with a curing time of 260 seconds. Upon exposure to the UV-light, the epoxy, OG142 will cure and bond tightly to the PMMA. Table 1 shows the process flow for the fabrication of the 1×2 Y-branch POF coupler showing the two-step and three-step molding processes.

Figure 6 shows the fabricated master mold, auxiliary mold, PDMS stamp and final 1×2 Y-branch coupler. The geometrical properties of the fabricated devices were characterized by using an inspection microscope. The Y-junction structure of both fabricated devices were investigated and compared. Figure 7 shows the close-up view of the Y-junction of the fabricated device. Figure 7(a) shows the Y-junction region for design 1 which used the normal two-step molding process. The Y-junction obtained using the normal two-step molding softlithographic process could not produce the required sharp Y-junction structure. Figure 7(b) shows the Y-junction region for design 2 which used the three-step molding process. It can be seen that the proposed three-step molding softlithographic process that adopted a simple auxiliary molding step has successfully produced a very sharp Y-junction structure. The PDMS mold or stamp replicated via this technique has enabled the replication of the Y-branch POF coupler and provided a good splitting properties for the coupling and splitting of light signal.

The optical characteristics of the fabricated device is obtained by measuring the insertion losses of the device. The light source used in the characterization is the FF-OS417 optical source from Advanced Fiber Solutions whereas the optical power meter is the OM210. The coupling of the polymeric waveguide with an external POF is achieved through butt-coupling of the external POF with the ends of the waveguide. This is done by utilizing an acrylic insert with U-grooves for input and output fiber alignment. Figure 8(a) shows the parts used for the waveguide and fiber alignment and attachment. The

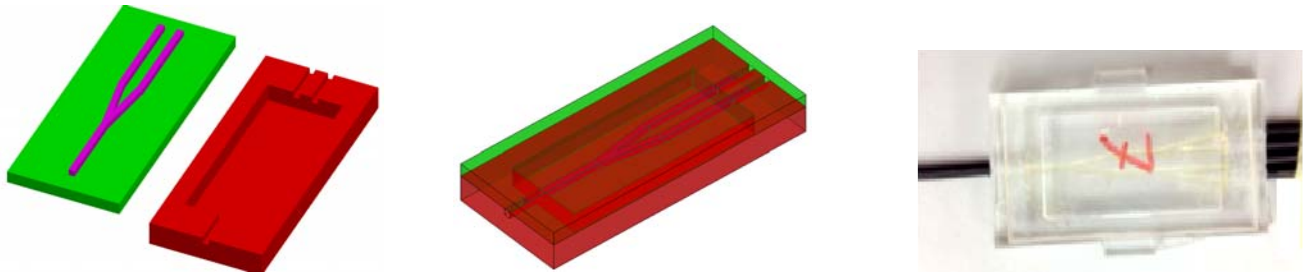


(a) (b) (c) (d)

Figure 6. Fabricated components for device fabrication, (a) master mold, (b) auxiliary mold, (c) PDMS stamp, (d) optical device.

(a) (b)

Figure 7. Close view of Y-junction region of the fabricated devices. (a) Design 1. (b) Design 2.



(a) (b) (c)

Figure 8. Fiber-waveguide alignment using acrylic insert, (a) device and insert, (b) insertion of device into acrylic insert, (c) assembled device.

completed polymeric waveguide device is inserted into the acrylic insert shown in Figure 8(b). Finally, input and output POFs are slotted into the U-grooves and butt coupled to the ends of the waveguides. Figure 8(c) shows the assembled 1×2 Y-branch POF coupler with the acrylic insert and external POFs. In order to reduce the coupling loss as much as possible, the cutting tool from *Ratioplast-Optoelectronics* (Germany), which produce a clean cut of the POF and hence requires no end polishing has been utilized. The additional insertion loss due to the POF is about 0.5 dB. Hence, the total loss introduced by the fiber-waveguide coupling is about 1 dB. The test wavelength is set at 650 nm. The effective input power Pin is set at 0 dB or 1 mW. The output power detected at both output ports are $P1 = 0.1513$ mW and $P2 = 0.1059$ mW respectively. The coupling ratio of the fabricated device is 58:42. The insertion losses of this device are 8.2 dB and 9.75 dB respectively whereas the excess loss is 5.89 dB.

5. CONCLUSION

A three-step molding softlithographic process for a 1×2 Y-branch POF has been proposed and demonstrated. The auxiliary molding step based on the use of a simple casting material has enabled a sharp Y-junction structure to be produced and replicated from a rigid PMMA master mold. The sharp Y-junction was easily reproduced by replicating the master mold feature onto a low viscosity and room temperature curable casting resin. The same features as those of the PMMA master mold was then transferred onto the final PDMS stamp. Geometrical features on the fabricated devices shows that the three-step molding process can be utilized to produce sharp Y-junction structure which cannot be simply be replicated via the normal two-step molding softlithographic process. The replicated optical device fabricated on a UV curable optical resin has been produced. Even though the losses are seemingly higher, the device is able to perform as a splitter. The proposed method based on the three-step molding softlithographic process will enable rapid replication of functional polymeric optical devices for not only a simple 3 dB coupler, but other niche devices such as asymmetric or variable coupling ratio devices.

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