Large core optical elastomer splitter fabricated by using 3D printing pattern

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Abstract
The design, fabrication and properties of the large core 1×2Y optical planar splitter using optical elastomers for its cladding and core is demonstrated. The splitters were designed by using the beam propagation method, optimized for the operation wavelength of 650 nm. The splitters were fabricated using an epoxy polymer pattern, fabricated by Stereolithography 3D printing technology. The dimensions of the splitters were optimized for assembling an optical fiber with a core diameter of 500 µm. The splitter shows optical losses around 1.48 dB at 650 nm, 1.18 dB at 850 nm, 1.82 dB at 1300 nm and 2.12 dB at 1550 nm.

Keywords Optical splitter · Large core waveguides · Optical elastomers · Beam propagation method · Stereolithography 3D printing technology

1 Introduction
The importance of and interest in short-distance optical communication up to 100 m is increasing due to the higher demand for high-speed communications. This communication can be realized by low-cost and high-speed optical systems using large core optical fibers. They have used polymer fibers called Plastic Optical Fiber (POF) and are operating in the visible spectrum, usually at red light, which is around 650 nm. These optics systems are used mainly in the transportation industry for multimedia transmission systems such as MOST (Multimedia Oriented System Transport), a passive star system for the vehicular control Byteflight system used to connect airbag systems with other control components in the intelligent safety integration system in BMW cars, or in Digital Domestic Bus (D2B) used in Mercedes and Jaguar vehicles which connect the DVD-player, back seat systems with the screens, navigation computer, car telephone, etc. (Grzemba 2011).

For the distribution of the optical signal, one of the most important devices is the optical splitter. Previously, plenty of methods used for the fabrication of splitters were developed, including face fiber couplers, polished couplers, or fiber fused combining (Ziemann et al. 2008). Optical splitters in the planar design are more efficient than fiber-based structures.
and methods used to fabricate these devices have already been described before. For example, the optical planar splitters with the input and output waveguide dimensions between hundreds of nanometers to 6 μm, which are compatible with single-mode silicon photonics technology, were presented in Sakai et al. (2002); Zhang et al. (2013). Optical planar splitters were also presented with dimensions compatible with the single (SM) and multimode (MM) optical fibers with a core up 9 μm (SM) and 50 or 62.5 μm (MM) (Zigang and Duan 2006; Rezem et al. 2017). These splitters are usually fabricated using ion-exchange in glass (Zigang and Duan 2006), the photolithography process (Bamiedakis et al. 2009), laser-direct writing, etc. (Wang et al. 2009). The above mentioned fabrication methods are complex and are also not appropriate for the fabrication of optical multimode planar large core splitters. Therefore, new efficient production methods and technological processes are being sought. For example, methods such as Laser LIGA technique mold (Klotzbuecher et al. 2003), injection molding (Takezawa et al. 1994), and hot embossing method using thermo-plastic resin (Mizuno et al. 2006) were presented. Properties of the optical splitters with a hollow taper region (Ehsan et al. 2010) were presented and Computer Numerical Control (CNC) machining using poly(methyl methacrylate) polymer substrate was described, creating a U-groove shape and a UV curing polymer for the core layer were applied (Ehsan et al. 2011; Prajzler and Zazvorka 2019). Large core splitters with a core dimension of 750 μm were reported (Prajzler et al. 2017a). U-groove substrates were fabricated by a 3D printer, Precision Desktop Objet30 Pro, and a VeroClear RGD810 polymer was used for the substrate and cladding layer. Norland Optical Adhesive UV photopolymer was used for the core layer. The above mentioned techniques are suitable for small batch production fabrication as well as for creating samples, but they are not suitable for mass production.

In this paper, we are going to present the properties of the large core planar splitter, fabricated by using a polymer mold. The mold is fabricated by using a 3D printed pattern with both a U-groove and a 1×2Y shape. Optical elastomers are used for the core and the cladding. The advantage of this fabrication procedure is the possibility of fabricating more U-groove molds, and after, fabricating optical splitters in larger amounts at the same time. Therefore, this solution will allow for easier and cheaper mass production. We did not use traditional POF during assembly, which has a polymethyl methacrylate core and fluorinated polymers cladding with a standard dimension of around 1 mm, but for assembly, we used MOLEX fiber with a core dimension of 500 μm (Fiber and datasheet: https://www.molex.com/webdocs/datasheets/pdf/en-us/1068000063_OPTICAL_FIBER.pdf). Large dimensions of the MOLEX fiber which were used, maintained the advantages of POF, allowing for an easy installation, using simple plug connectors, large acceptance and high flexibility. Other advantages of this fiber are higher temperature resistance (operating temperature −65° to +300 °C, compared to common POF which is from −55° to +70 °C) and also a wider operating wavelength range (380 nm–2200 nm) when compared with POF which only allows light in the visible spectrum to be transmitted.

2 Design of the proposed splitter

The structure of the design splitter is shown in Fig. 1. Silicon optical elastomer LS-6943 (NuSil) based on a dimethyl diphenyl silicone copolymer was used for the core and polydimethylsiloxane Sylgard 184 (Dow Corning) was used as the cladding layer. The optical signal is coupled into large core fibre with the core diameter of 550 μm. Light
enters into the input part of the splitter $P_{in}$ and then light is equally divided in the taper region $d$ into two output fibers through the S-bend waveguides $L_s$ with optical power $P_{out1}$ and $P_{out2}$. Output waveguides are connected to the same large core optical fibers used on the input.

Before designing and optimizing the dimensions of the optical splitter, we measured the refractive index values for the materials used by dark mode spectroscopy using a prism-coupler by Metricon 2010 (Metricon Corporation: www.metricon.com, 2010) and measurements were taken at six wavelengths; 532, 654.2, 846.4, 1308.2, 1549.1 and 1652.1 nm. The values of the refractive indices of the LS-6943 elastomer differ slightly from the values provided by the polymer supplier, NuSil. We expect that this difference was caused by the slightly different way the polymer was prepared (see Fig. 2a). The values of the refractive indices for elastomer Sylgard 184 are very different from the values given by the supplier (see Fig. 2a). We think that the supplier provided incorrect data. We have obtained the same results in our previous published results (Prajzler et al. 2017b). As it was expected, it was also confirmed that the LS-6943 elastomer used for waveguide core has a higher refractive index than the Sylgard 184 elastomer used for the cladding layer.

Because the refractive indices values were measured only at six wavelengths, we used approximation to determine the values outside these measured wavelengths. For that, we chose the Sellmeier formula with an infrared correction (Prajzler et al. 2020):

![Fig. 1 Schematic of the large core splitter with the elastomers core and cladding layers](image)

![Fig. 2 Optical properties of the applied materials, LS-6943 and Sylgard 184, a Refractive indices, b Absorption spectra](image)
where $n$ is the refractive index, $\lambda$ is the wavelength and $A$, $B$, $C$ and $D$ are experimentally determined Sellmeier coefficients. This approximation was chosen because we previously proved that this approximation method for our applied measurements were the most suitable (Prajzler et al. 2020). The experimentally determined Sellmeier coefficients are depicted in Table 1.

The calculated values of the refractive indices are summarized in Table 2.

To verify the suitability of the optical elastomers used (core LS-6943, cladding Sylgard 184) we also measured the absorption spectra. The measurement was done by the UV–VIS-NIR spectrophotometer (UV-3600, Shimadzu) in the spectral range from 250 to 2100 nm. For that, we fabricated a thick LS-6943 and Sylgard 184 sheet, where the fabrication procedures were similar to the splitter (the ratio mixture of the both elastomers was 10:1 of the A and B agents, stirred and then poured into a desiccator for 60 min, hardening for 4 h at 65 °C). Figure 2b shows that both elastomers LS-6943 (core material) and Sylgard 184 (cladding) follow similar shapes of the absorption spectra.

The low values of optical absorption in the visible spectrum for the core elastomer LS-6943 proved that this material is suitable for realization waveguide structure for the operating wavelength of 650 nm, for which the splitters were designed. Absorption spectra in the infrared region at wavelengths 850 and 1300 nm are also low, which means that the structure can be used for multimode optical communications.

Geometrical dimensions of the $1 \times 2Y$ splitter was designed by using the Beam Propagation Method using BeamPROP™ software (RSoft photonics suite) and the optimization of the dimensions were done by applying MOST tools, (RSoft’s, Multi-Variable Optimization and Scanning Tool). The dimensions were optimized for connecting the optical fibers at both the input and output. The optical fibers had a 500 µm core and a 550 µm thick cladding layer. Optimization was done for the 2D dimensional channel with a multimode source operating at the wavelength of 650 nm with the refractive indices $n_f = 1.4277$ LS-6943 (core) and $n_s = 1.4109$ Sylgard 184 (cladding) (see Table 2). The result of the simulation with the branching angle $\Omega$ is given in Fig. 3a and the optimized splitter with the refractive

\begin{equation}
\frac{n^2(\lambda)}{\lambda^2} = A + \frac{B\lambda^2}{\lambda^2 - C} - D\lambda^2
\end{equation}

Table 1 Sellmeier coefficients with an infrared correction calculated at six wavelengths (532, 654.2, 846.4, 1308.2, 1549.1 and 1652.1 nm)

| Elastomer | A       | B       | $C \times 10^4$ (µm²) | $D \times 10^3$ (µm⁻²) |
|-----------|---------|---------|-----------------------|------------------------|
| Sylgard 184 | 1.52090 | 0.4446  | 0.0232960             | 0.0021032              |
| LS-6943    | −75.4502 | 77.4584 | 0.0001688              | 0.0020851              |

Table 2 Refractive indices of Sylgard 184 cladding and LS-6943 core calculated by the Sellmeier formula with an infrared correction from data measured by Metricon 2010

| $\lambda$ (nm) | 532 | 650 | 850 | 1300 | 1550 |
|----------------|-----|-----|-----|------|------|
| Sylgard 184 $n_s$ | 1.4159 | 1.4109 | 1.4067 | 1.4029 | 1.4017 |
| LS-6943 $n_f$ | 1.4331 | 1.4277 | 1.4229 | 1.4186 | 1.4173 |
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Figure 4a shows a graphical display of the simulation for the optimized dimensions of the contour of the splitter and Fig. 4b which shows the propagation of the signal at 650 nm. The figure shows that the optical signal entering into the input waveguide \( P_{in} \) passes to the tapered part of the splitter and then the optical signal is symmetrically divided into the two S-bend waveguides. Finally, the optical splitter ends with two straight output waveguides \( P_{out1} \) and \( P_{out2} \).

The value of the branching angle \( \Omega \) was optimized for dividing the wavelength 650 nm symmetrically, but we also simulated the power distribution by using the BPM method for the next four wavelengths (532, 850, 1300 and 1550 nm). The optical signal at wavelength 532 nm is divided into the ratio 44.0: 56.0% (not presented in Fig. 4). Figure 4a shows a graphical display of the signal propagation and Fig. 4b shows the propagation of the optical signal at wavelength 650 nm, where the optical signal is divided symmetrically (50.0: 50.0%). Figure 4c shows the result at wavelength 850 nm and shows that the optical signal is divided into a slightly asymmetrical ratio (51.1%: 48.9%). Figure 4d shows the result at wavelength 1300 nm and Fig. 4e shows the result at wavelength 1550 nm. The optical signal at wavelength 1300 nm is divided into the ratio 55.0: 44.9% and the optical signal at wavelength 1550 nm is divided into the ratio 58.4: 41.7% respectively.

3 The process of preparing the large core waveguides

Optical splitters were fabricated using commercially available optical elastomers, based on a dimethyl diphenyl silicone copolymer LS-6943 (NuSil) for the core layer and polydimethylsiloxane Sylgard 184 (Dow Corning) for the cladding layer. The splitters were fabricated by casting, where the negative mold with the shape of the 1×2Y design was printed using the Masked Stereolithography printing process by an Original Prusa SL1 3D printer with a 5.5” high-resolution LCD display with a physical resolution of 2560×1440 pixels, and a layer height resolution of 0.01 mm. The high-quality UV photosensitive 405 nm liquid resin was applied. Separable casting molds used for keeping enough layer thickness on
the negative mold was printed using Acrylonitrile butadiene styrene (ABS) by an Original Prusa i3 MK2 3D printer. The process is presented step by step in Fig. 5.

The printed 1 × 2 Y negative mold was put into the ABS form (see Fig. 5a). Then a separator (Ambersil’s Formula 10) was applied to the mold so the hardened layer could be easily separated from the mold. Then the Sylgard 184 elastomer was mixed in the ratio of 10:1 (the A and B agents) and the mixtures were stirred and then poured into a desiccator for 60 min. After, the Sylgard 184 mixture was poured into the form (see Fig. 5b) and then hardened for 4 h at 65 °C.

The hardened Sylgard 184 substrate with U-groove in the desired splitter pattern was then separated from the mold and it was inserted into a casting form with holes for fibres (see Fig. 5c). After that, the one input and two output fibers were assembled (see Fig. 5d). We used 15 cm long pigtails fibers, Polymicro Optical Fibers (MOLEX), with a synthetic fused silica core and polyimide cladding with a 500 µm core and 550 µm cladding (FIP500550590, Polymicro TECHNOLOGIES) (Fiber and datasheet :www.molex.com,webdocs,datasheets.pdf,en-us,1068000063_OPTICAL_FIBER.pdf) with FC/PC connectors. Then, the LS-6943 elastomer used for the core layer was mixed (the ratio of 10:1 of the A and B agents) and the mixtures were stirred and then poured into a desiccator for
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60 min. After, the LS-6943 mixture was poured into the waveguide Sylgard 184 U-groove channels and hardened for 4 h at 65 °C in the oven (see Fig. 5e). Finally, the Sylgard 184 cladding was applied (see Fig. 5f). The cladding Sylgard 184 layer was prepared with the same fabrication procedure as the Sylgard 184 substrate for the U-groove (mixed the A and B agents in the ratio of 10:1, stirred and then poured into a desiccator for 60 min, hardening for 4 h at 65 °C).

4 Results

The dimension and quality of the 1×2Y mold pattern was checked by a KEYENCE microscope, series VHX-6000. Figure 6a shows the cross-section of the input U-groove for assembling the input fiber. Figure 6b, c, d show a detailed top view photo of the Sylgard 184 substrate with a visible U-groove for pouring the LS-6943 core layer, while Fig. 6b shows the input of the U-groove waveguide part, following with the taper region enlarging in the direction of the optical signal propagation. Figure 6c shows the U-groove of the taper region followed by two output waveguides. Figure 6d shows the U-groove of the two output waveguides. Figure 6e shows the cross-section of the U-groove outputs for assembling the two output fibers.

Figure 7 shows the final 1×2Y optical splitter assembled with the input/outputs large core fibers, LS-6943 core and Sylgard 184 substrate and cladding. The optical visual check shows that the dimension of the splitter is very similar to the optimized design layout and there were no visible defects.

Figures 6 and 7 proved that the dimensions of the fabricated 3D negative 1×2Y mold fabricated from epoxy polymer and also the dimensions of the final 1×2Y splitter fabricated from optical elastomers correspond to the design splitter layout. The surface...
Optical losses were measured at red light at 650 nm and infrared wavelengths at 850, 1300 and 1550 nm. For that, we used four OFLS lasers from the company Safibra: 650 nm (OFLS-5-FP-650), 850 nm (OFLS-6-LD-850), 1300 nm (OFLS-6CH, SLED-1300) and 1550 nm (OFLS-5-DFB-1550). Optical power was measured by using a Thorlabs PM200 powermeter with a silicon probe (S151C) for the wavelengths 650 and 850 nm or an indium gallium arsenide probe (S155C) for the wavelengths 1300 and 1550 nm. The measurement started with determining the reference optical power $P_{\text{ref}}$ coming from the laser and passing through the reference waveguide. The reference waveguide was fabricated using the same procedure as the optical splitter with the same materials for the core and the cladding layer. The samples were also assembled with the same input and output fibers (15 cm long pigtails) with FC/PC connectors. After that, we measured the optical output powers $P_{\text{out1}}$ for the right output branch and $P_{\text{out2}}$ for the left output branch of the splitters, respectively.
Then we calculated the optical losses for the output branches $P_{\text{branch1}}$ and $P_{\text{branch2}}$ using Eqs. (2):

$$P_{\text{branch1}} = -10 \frac{P_{\text{out1}}}{P_{\text{ref}}} \quad P_{\text{branch2}} = -10 \frac{P_{\text{out2}}}{P_{\text{ref}}} \quad [\text{dB}]$$

(2)

The optical losses $\alpha$ were calculated from Eq. (3):

$$\alpha = -10 \frac{P_{\text{out1}} + P_{\text{out2}}}{P_{\text{ref}}} \quad [\text{dB}]$$

(3)

and we also calculated the uniformity $A_u$ (Eq. 4) using the following equations:

$$A_u = 10 \frac{P_{\text{out1}}}{P_{\text{out2}}} \quad [\text{dB}]$$

(4)

The measurements were done at room temperature for two samples and the results are summarized in Table 3.

Table 3 Measurement results of the optical losses of the 1 × 2Y optical splitters

| Sample | #1 | #2 |
|--------|----|----|
| $\lambda$ (nm) | 650 | 850 | 1300 | 1550 | 650 | 850 | 1300 | 1550 |
| $P_{\text{out1}}$ (μW) | 142.0 | 23.0 | 140.0 | 7.0 | 127.0 | 20.1 | 122.0 | 7.3 |
| $P_{\text{out2}}$ (μW) | 114.6 | 19.3 | 108.0 | 5.7 | 132.0 | 20.7 | 121.0 | 6.5 |
| $P_{\text{ref}}$ (μW) | 364.0 | 55.5 | 377.0 | 22.5 | 364.0 | 55.5 | 377.0 | 22.5 |
| $P_{\text{branch1}}$ (dB) | 4.09 | 3.83 | 4.30 | 5.07 | 4.57 | 4.41 | 4.90 | 4.89 |
| $P_{\text{branch2}}$ (dB) | 5.02 | 4.59 | 5.43 | 5.96 | 4.41 | 4.28 | 4.94 | 5.39 |
| Uniformity—$A_u$ (dB) | 0.93 | 0.76 | 1.13 | 0.89 | 0.89 | 0.86 | 1.24 | 0.61 |
| Optical losses—$\alpha$ (dB) | 1.52 | 1.18 | 1.82 | 2.48 | 1.48 | 1.34 | 1.91 | 2.12 |
loss of 3.45 dB at 650 nm. The core diameter of the splitter was 0.98 mm and the length was around 45 mm. Our previously presented splitters have a core dimension of 1 mm, which were optimized for the visible spectrum and had optical losses of 4.3 dB and 5.0 dB at 650 nm (Prajzler et al. 2014). Next, our splitter had a dimension optimized for assembling large core input/output FG910LEC (Thorlabs Inc.) multimode optical fiber having a core diameter of Ø910 µm and allowed for the transmission of the signal not only in visible, but also in the infrared range of the spectrum, and optical losses were 8.2 dB at 850 nm, 6.1 dB at 1310 nm and 6.2 dB at 1550 nm (Prajzler et al. 2016).

5 Conclusion

We demonstrated the fabrication process and properties of large core multimode optical polymer planar 1 x 2Y splitters with a LS-6943 elastomer core and a Sylgard 184 elastomer cladding. The splitter was designed using the Beam Propagation Method using BeamPROP software and the dimensions were optimized for the wavelength of 650 nm and for the assembled input and output optical fibers with the core diameter of 500 µm. Splitters were fabricated using a negative mold printed on a 3D printer from epoxy polymer, by using the masked stereolithography printing process. The splitter had optical losses of 1.48 dB with uniformity around 0.89 dB at the optimized operating wavelength 650 nm. The splitters also had low optical losses at the infrared spectrum of 1.34 dB at 850 nm and 1.91 dB at 1300 nm.

The presented results proved that we have developed an easy and feasible solution for the fabrication of large core optical splitters, optimized for visible light but which are also able to operate in infrared wavelengths which are used in optical communication systems.

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