Large Core Optical Elastomer Splitter Fabricated by Using 3D Printing Pattern

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Research Article

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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 1x2Y optical planar splitter using optical elastomers for cladding and core is demonstrated. The splitters were designed by beam propagation method optimized for operation wavelength 650 nm. The splitters were fabricated using epoxy polymer pattern fabricated by Stereolithography 3D printing technology. The dimensions of the splitters were optimized for assembling optical fiber with core diameter 500 µm. The splitter shows optical losses around 1.48 dB at 650 nm, 1.18 dB at 850, 1.82 dB at 1300 nm and 2.12 dB at 1550 nm at room temperature.

Keywords:
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1 Introduction

The importance and interest of 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 a red light around 650 nm. These optics systems are used mainly in the transportation industry for multimedia transmission systems such as MOST (Multimedia Oriented System Transport), passive star system for vehicular control Byteflight system used in connects airbag systems with other control components in the intelligent safety integration system in BMW cars or Digital Domestic Bus (D2B) used in Mercedes and Jaguar vehicles connect the DVD-player, back seat systems with screens, the navigation computer, car telephone and etc. [1].

For the distribution of the optical signal, one of the most important devices are optical splitters. Previously there were developed plenty of methods used for the fabrication of the splitter including face fiber couplers, polished couplers, or fiber fused combining [2]. Optical splitters in the planar design are more efficient than fiber-based structures and there have been already described methods used for the fabrication of these devices. The optical planar splitters with dimensions compatible with single-mode silicon photonics technology, where the dimension of the input and output waveguides are around hundreds of manometers up to 6 µm [3, 4]. They were also presented optical planar splitters with dimensions compatible with the single (SM) and multimode (MM) optical fibers with the core up 9 µm (SM) and 50 or 62.5 µm (MM) [5, 6]. These splitters are usually fabricated by ion-exchange in glass [5], photolithography process [7], laser-direct writing and etc. [8]. Above mentioned methods fabrication methods for the realization of the large core optical planar splitters are not appropriate. Therefore, new effective fabrication methods and technological processes were invented. For examples, there were presented methods such as Laser LIGA technique mold [9], injection molding [10], hot embossing method using thermo-plastic resin [11]. It was presented properties of the optical splitters with hollow taper region [12] and it was also described Computer Numerical Control (CNC) machining using poly(methyl methacrylate) polymer substrate creating Y-groove shape and UV curing polymer for the core layer were applied [13, 14]. Similar fabrication methods were described in [15] but instead of CNC machining into polymer substrate, Y-groove shape was fabricated by 3D printing technique. Above mention techniques are suitable for fabrication for piece production of samples, but not suitable for mass production.

In this paper we are going to report about properties of the large core planar splitter fabricated by using polymer mold. The mold is fabricated by 3D printing pattern with U-groove and 1x2Y shape and optical elastomers are used for the core and the cladding. This solution allows for easy and cheap mass production. We did not use traditional POF for assembling which has polymethyl methacrylate core and fluorinated polymers cladding with a standard dimension of around 1 mm but for assembling we used MOLEX fiber with the dimension of the core 500 μm [16]. Large dimensions of the used MOLEX fiber maintain the advantage of POF allowing easy installation, using simple plug connectors, large acceptance, high flexibility. Other advantages of this fiber are higher temperature resistance (operating temperature -65° to +300°C, compared to common POF -55° to +70°C) and also wider operating wavelength range (380 nm – 2 200 nm) with POF comparison which allows transmitting light only in the visible spectrum.

2 Design of the proposed splitter

The structure of the design splitter is shown in Fig. 1. Optical elastomer LS-6943 (NuSil) was used for the core and Sylgard 184 (Dow Corning) was used as the cladding layer. The optical signal is coupled into large core fibre with the core diameter 550 μm and 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 fiber through 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.

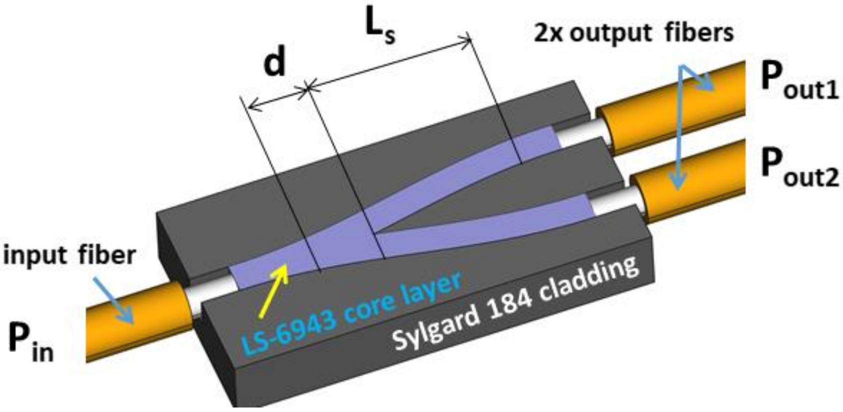

Fig. 1. Schematic of the large core splitter with elastomers core and cladding layers.

Before designing and optimizing the dimensions of the optical splitter, we measured the refractive index values for the used materials by dark mode spectroscopy using prism-coupler by Metricon 2010 [17] and measurement was done for 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 values providing by the polymer supplier NuSil. We expect that this difference is caused by a slightly different way of preparing the polymer (see Fig. 2(a)). The values of refractive indices for elastomer Sylgard 184 are very different from the values given by supplier (see Fig. 2(a)) we think that is due to providing wrong data by supplier. We have obtained same results in our previous published results [18]. As it was expected, it was also confirmed that the LS-6943 elastomer used for waveguide core has higher refractive index than the Sylgard 184 elastomer used for the cladding layer.

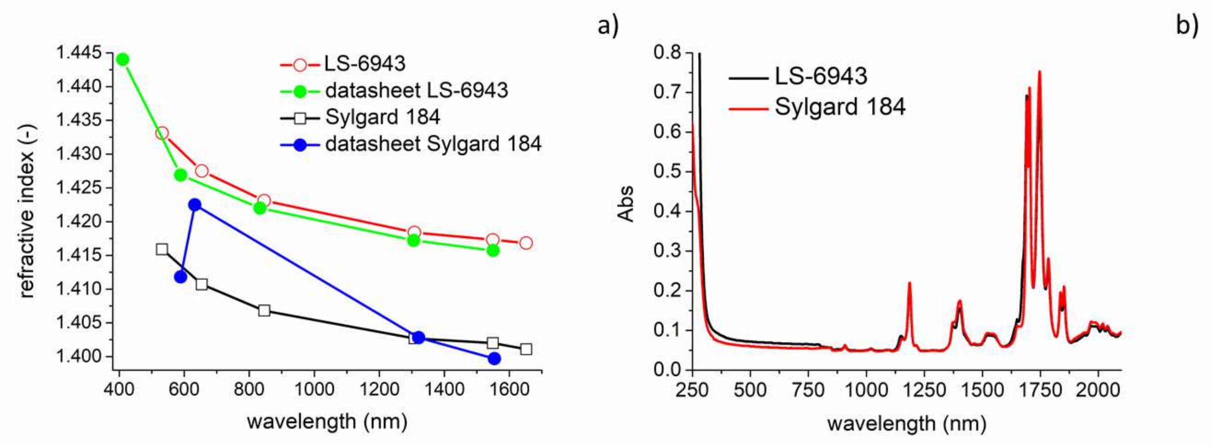

Fig. 2. Optical properties for the applied materials LS-6943 and Sylgard 184, (a) Refractive indices, (b) Transmission spectra.

Because the refractive indices values were measured only at six wavelengths, we used the approximation to determine the values to outside these measured wavelengths. For that we choose the Sellmeier formula with an infrared correction [19]:

$$n^2(\lambda) = A + \frac{B\lambda^2}{\lambda^2 - C} - D\lambda^2 \qquad (1)$$

where n is the refractive index, λ is the wavelength and A, B, C and D. This approximation was chosen because we previous proved that this approximation method is for our applied measurement the most suitable [19]. The experimentally determined Sellmeier coefficients are depicted in Tab. 1.

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

elastomer	A	B	$C\cdot10^1$ (μm^2)	$D\cdot10^3$ (μm^{-2})
Sylgard 184	1.5209	0.4446	0.023296	0.0021032
LS-6943	-75.4502	77.4584	0.0001688	0.0020851

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

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

λ (nm)	532	650	850	1300	1550
Sylgard 184 n_s (-)	1.4159	1.4109	1.4067	1.4029	1.4017
LS6943 n_f (-)	1.4331	1.4277	1.4229	1.4186	1.4173

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

The low values of optical absorption in visible spectrum for the core elastomer LS-6943 proved that this material is suitable for realization waveguide structure for operating wavelength of 650 nm for which were the splitters designed. Absorption spectra in the infrared spectrum interesting for optics communications (850 and 1300 nm) are also low enough.

Geometrical dimensions of the 1x2Y splitter was designed by 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 at the input and output with the optical fibers having 500 μm core and cladding layer thick 550 μm. Optimization was done for the 2D dimensional channel with a multimode source operating at the wavelength 650 nm with the refractive indices $n_f = 1.4277$ LS-6943 (core) and $n_c = 1.4109$ Sylgard 184 (cladding) (see Tab. 2). The result of the simulation of the branching angle Ω is given in Fig. 3(a) and the optimized splitter with the refractive index profile is shown in Fig. 3(b). The optimal value of the branching Ω angle at 650 nm is 1.112° as is shown in Fig. 3(a). At this angle occurs a symmetrical division of the optical power between the output waveguides P_{out1} and P_{out2}; the length of the tapered part of the splitter d will be 19.15 mm and that of the s-bend part of the splitter L_s will be 22.15 mm.

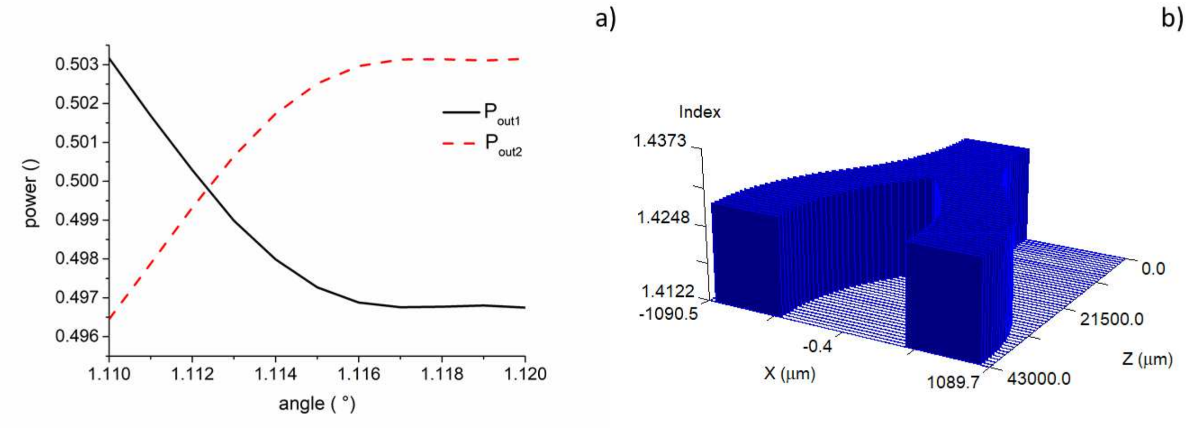

Fig. 3. (a) Dependence of the outputs P_{out1} and P_{out2} normalized optical power to the branching angle Ω, (b) Refractive index profile for the optimized dimensions 1x2Y Sylgard 184/LS-6943.

Fig. 4(a) shows a graphical display of the simulation for optimized dimensions of the contour of the splitter and Fig. 4(b) shows the propagation of the signal at 650 nm. The figure shows that the optical signal entering into the input waveguide P_{in} passing 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 is ended with two straight output waveguides P_{out1} and P_{out2}.

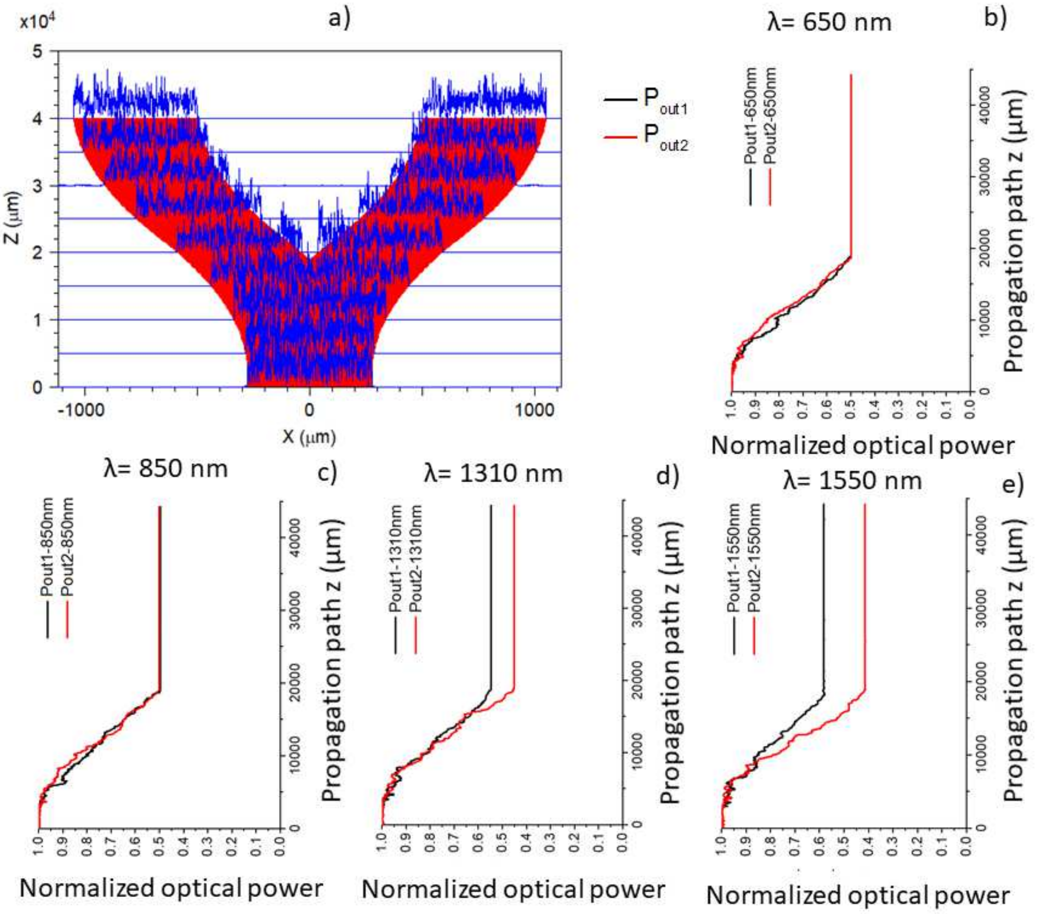

Fig. 4. Normalized optical signal propagation of the optimized 1x2 Y splitter, (a) graphical display of the signal propagation and signal propagation for wavelengths (b) 650 nm (n_f= 1.4277, n_s= 1.4109), (c) 850 nm (n_f= 1.4229, n_s=1.4068), (d) 1300 nm (n_f= 1.4186, n_s=1.4029), (e) 1550 nm (n_f= 1.4173, n_s=1.4017).

The value of the branching angle *Ω* was optimized for symmetrical dividing for wavelength 650 nm but we also simulated the power distribution by using the BPM method for the next four wavelengths (532 nm not presented in Fig. 4, 850, 1310 and 1550 nm). These simulation results are shown in Figs. 4, while Fig. 4(c) shows the propagation of the optical signal at wavelengths 850 nm, Fig. 4(d) shows results at 1300 and Fig. 4(d) shows results at 1550 nm respectively. The simulation shows that optical signal at 850 nm is divided slightly asymmetrical (51.1% : 48.9%), but for the longer wavelengths (1310 and 1550 nm) and the shortest one (532 nm) is that division more asymmetrical (44.0% : 56.0%).

3. The process of preparation of the large core waveguides

Optical splitters were fabricated using commercially available optical polydimethylsiloxane elastomers LS-6943 (NuSil) for the core layer and Sylgard 184 (Dow Corning) for the cladding layer. The splitters were fabricated by casting, where the negative mold with the shape of the design 1x2Y motive was printed using Masked Stereolithography printing process by Original Prusa SL1 3D printer. 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 Original Prusa i3 MK2 3D printer. The process is presented step by step in Fig. 5.

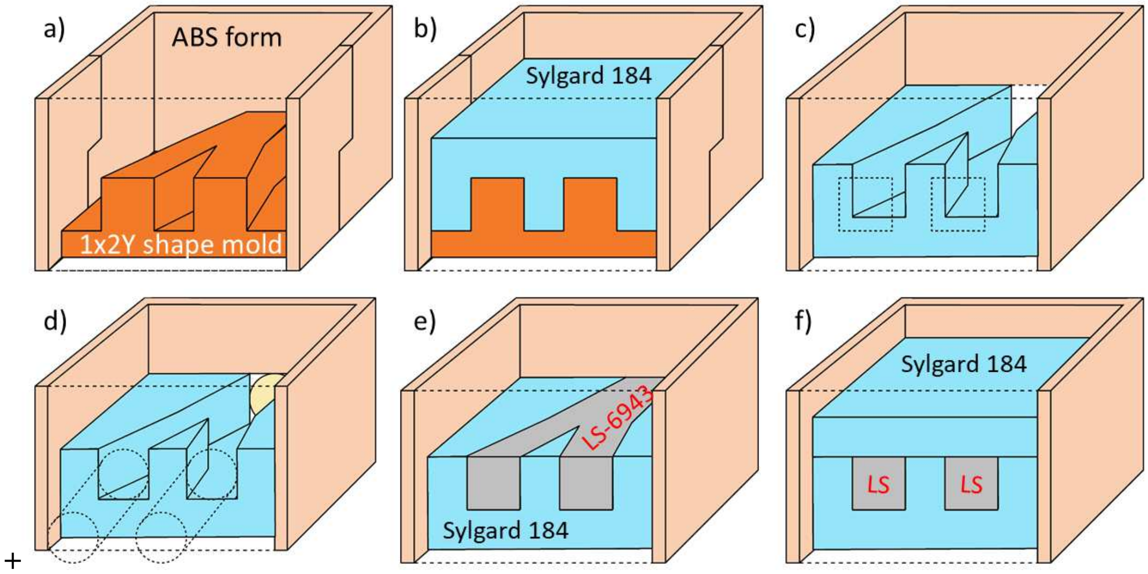

Fig. 5. Fabrication process for the optical splitters, (a) negative epoxy mold with required pattern inserted in ABS form, (b) negative mold poured with PDMS Sylgard 184 elastomer – fabrication of the substrate, (c) separation of the PDMS substrate with 1x2Y shape from the mold, turn upside down and insertion into ABS form, (d) assembling input and output fibers, (e) filling up the core LS-6943 elastomer layer in PDMS U-groove, (f) filling up Sylgard 184 PDMS cover layer.

Printed negative 1x2Y mold was put into ABS form (see Fig. 5(a)). Then a separator (Ambersil's Formula 10) was applied to the mold for the hardened layer could be easily separated from the mold. Then the Sylgard 184 elastomer was mixed in the ratio 10:1 (the A and B agents) and the mixtures were stirred and then evacuated in a desiccator for 60 minutes. After that Sylgard 184 mixture was poured into form (see Fig. 5(b)) and it was hardened for 4 hours 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. 5(c)). After that the one input and two output fibers were assembled (see Fig. 5(d)). We used 15 cm long pigtails fibers Polymicro Optical Fibers (MOLEX) with the synthetic fused silica core and polyimide cladding with the core 500 µm and cladding 550 µm (FIP500550590, Polymicro TECHNOLOGIES) [16] with FC/PC connectors. Then LS-6943 elastomer used for the core layer was mixed (the ratio 10:1 of the A and B agents) and the mixtures were stirred and then evacuated in a desiccator for 60 minutes. After that LS-6943 mixture was poured into waveguide Sylgard 184 U-groove channels and hardened for 4 hours 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 some way as Sylgard 184 substrate for the U-groove (mixed the A and B agents in the ration 10:1, stirred and then evacuation in a desiccator for 60 minutes, hardening 4 hours at 65°C).

4 Results

The dimension and quality of the 1x2Y motive mold pattern was checked by a KEYENCE microscope VHX-6000 series. Fig. 6(a) shows the cross-section of the input U-groove for assembling input fiber. Figs. 6(b, c, d) show a detailed top view photo of the Sylgard 184 substrate with visible U-groove for pouring LS-6943 core layer, while Fig. 6(b) shows input the U-groove waveguide part following with the taper region enlarge in the direction of optical signal propagation. Fig. 6(c) shows the U-groove of the taper region followed by two output waveguides and Fig. 6(d) shows the U-groove of the two output waveguides. Fig. 6(e) shows the cross-section of the outputs U-groove for assembling two output fibers.

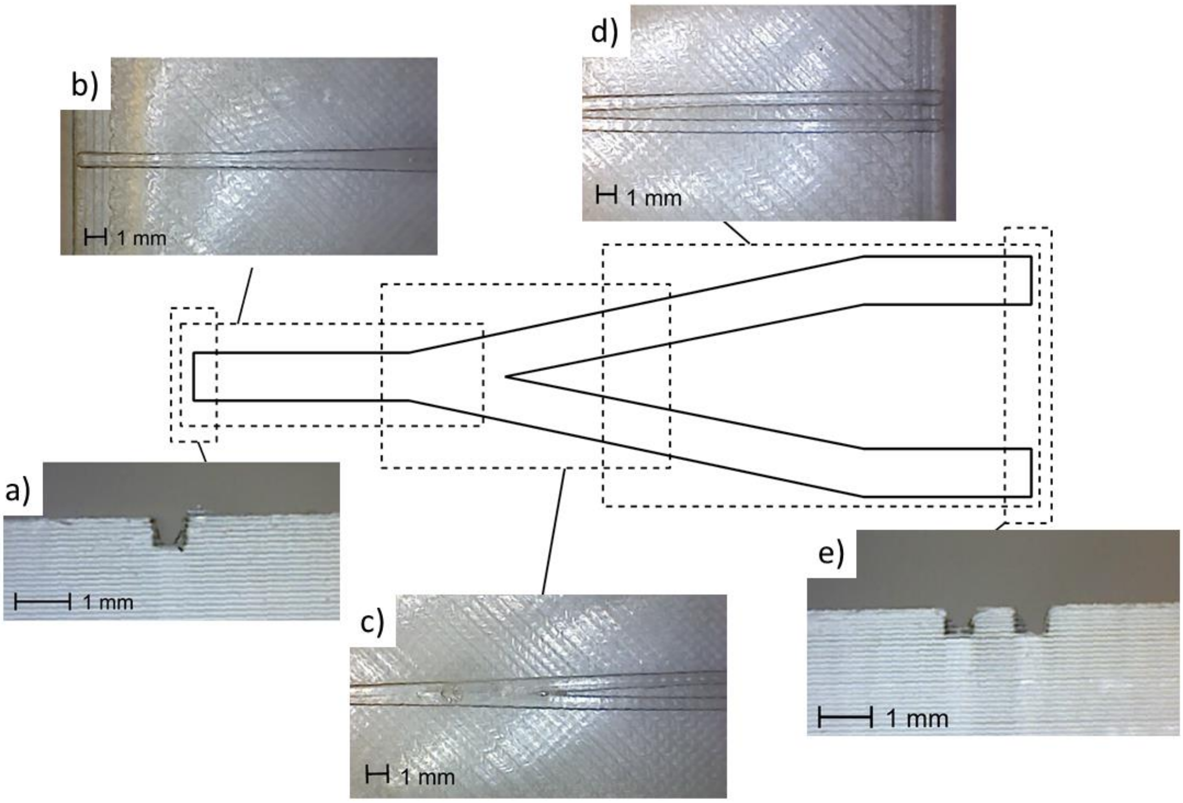

Fig. 6. Detailed image of 1x2Y Sylgard 184 substrate prepared of the assembling one input, two outputs fibers and pouring LS-6943 elastomer core layer. (a) input cross-section view, top view of the (b) input part, (c) taper region with two output waveguides, (d) two output waveguides, (e) cross-section view of the two outputs waveguides.

Fig. 7 shows final 1x2Y 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 not visible defects.

Fig. 7. Image of the fabricated 1x2Y splitter in 3D-printed ABS form.

Optical losses were measured at the red light at 650 nm and infrared wavelengths at 850, 1300 and 1550 nm. For that we used four lasers OFLS from Safibra company lasers 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 powermeter Thorlabs PM200 with silicon probe (S151C) for wavelengths 650 and 850 nm or indium gallium arsenide probe (S155C) for wavelengths 1310 and 1550 nm. The measurement started with determining the reference optical power P_{ref} coming from the laser and passing through the reference waveguide. The reference waveguide was fabricated the same procedure as an 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 power P_{out1} for the right output branch and P_{out2} for the left output branch and the optical losses α were then calculated from equation (2):

$$\alpha = -10 \log \frac{P_{out1} + P_{out2}}{P_{ref}} \; [dB] \qquad (2)$$

We also calculated the uniformity A_u (equation 3) using following equations:

$$A_u = 10 \log \frac{P_{out1}}{P_{out2}} \; [dB] \qquad (3)$$

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

Tab. 3. Measurement results of optical losses of optical splitter 1x2Y at room temperature.

sample	# 1				# 2			
wavelengths - λ (nm)	650	850	1300	1550	650	850	1300	1550
optical losses - α (dB)	1.52	1.18	1.82	2.48	1.48	1.34	1.91	2.12
uniformity - A_u (dB)	0.93	0.76	1.13	0.89	0.89	0.86	1.24	0.61

The measurement showed that the lowest optical losses were 1.18 dB (sample # 1) and 1.34 dB sample # 2 at 850 nm. As mention before optical splitter were design for wavelengths 650 nm and optical losses at this wavelength was also low 1.52 dB (sample # 1) and 1.47 dB (sample #2). Optical losses for wavelengths 1300 nm and 1550 nm were higher but for practical applications these values are usable. The losses were lower than 1.91 dB at 1300 nm and 2.48 dB at 1550 nm. The uniformity for optimized wavelength 650 nm was around 0.9 dB.

Properties of the several large core splitters have been previously published and the properties here presented splitter are comparable with them. The most of these optical splitters were assembled with POF fibres with dimension of the 1 mm and were optimized for visible light. Ehsan et al. 2011[13] reported on NOA63 polymer core and acrylic cladding splitter with losses 7.8 dB at 650 nm and Klotzbucher et al. 2003 [9] reported on splitters fabricated from two different resins and they achieved insertion optical losses around 6 dB at 660 nm. Takezawa et al. 1994 [10] reported on Y-branching plastic optical waveguide with low access losses 1.91 dB at 660 nm and Park et al. 2011 [20] reported on properties low-cost 1x2 plastic optical beam splitter using a v-type angle polymer waveguide for the automotive network with optical losses 3.45 dB at 650 nm. Our previous presented splitters optimized for visible spectrum had optical losses 4.3 dB and 5.0 dB at 650 nm [21] and for infrared wavelengths 8.2 dB at 850 nm, 6.1 dB at 1310 nm and 6.2 dB at 1550 nm [22].

5 Conclusion

We demonstrated fabrication process and properties of large core multimode optical polymer planar 1x2Y splitters with LS-6943 elastomer core and Sylgard 184 elastomer cladding. The splitter was designed by beam propagation method using BeamPROP software and dimension was optimized for wavelength 650 nm and for the assembling on input and outputs 500 µm core optical fibers. Splitters were fabricated using negative mold printed of 3D printer from epoxy polymer by MSLA (Masked Stereolithography) printing process. The splitter had the optical losses 1.48 dB with uniformity around 0.9 dB at optimized operating wavelength 650 nm and the splitters had also low optical losses at infrared spectrum 1.18 dB at 850 nm and 1.82 dB at 1300 nm.

The presented results proved that we have developed easy and feasible solution fabrication procedure for fabrication large core optical splitter optimized for visible light but the splitter it is also possible operate in infrared wavelength using in optical communication system.

Acknowledgments

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Figures

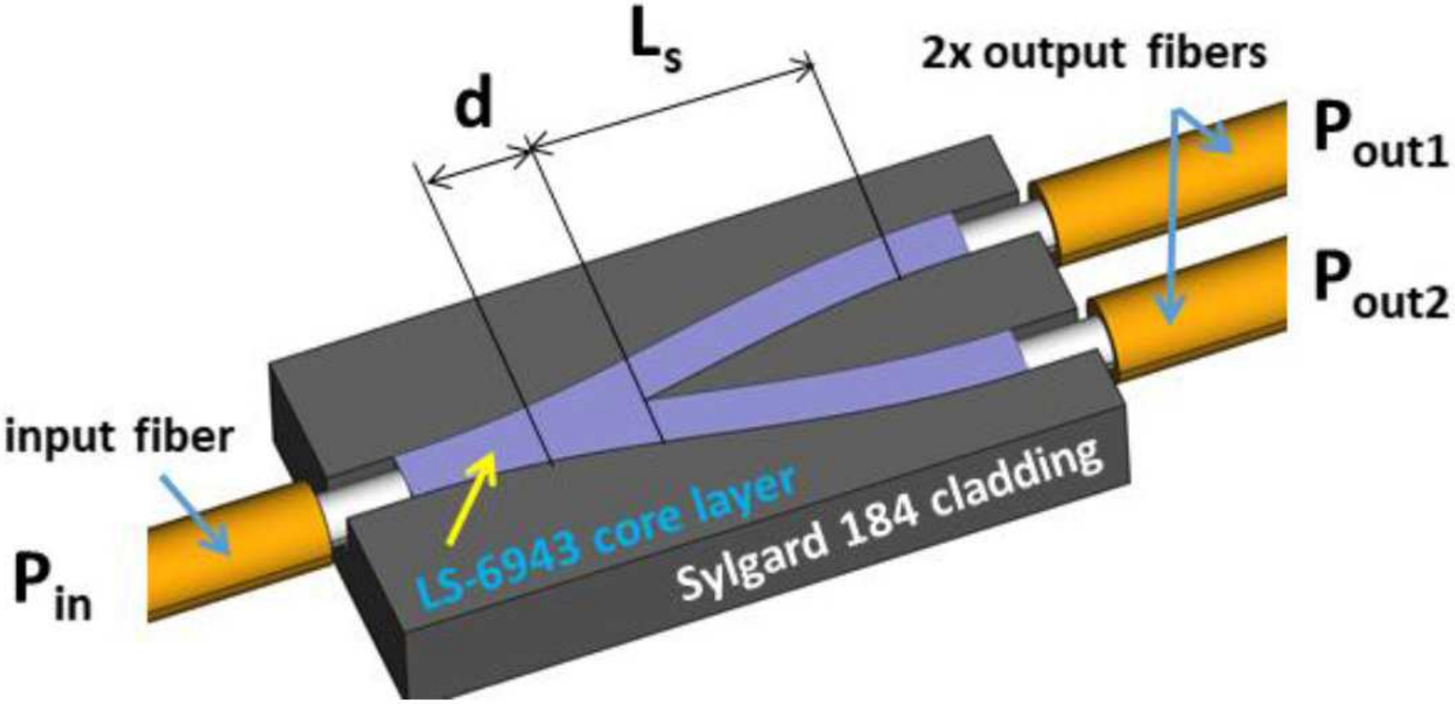

Figure 1

Schematic of the large core splitter with elastomers core and cladding layers.

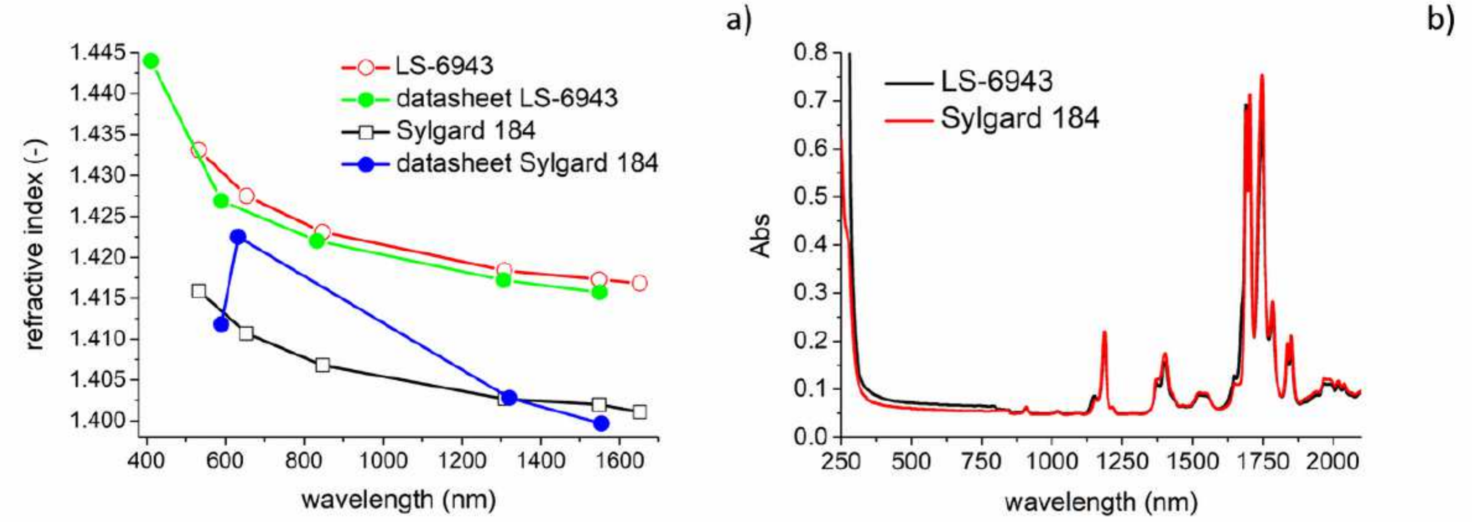

Figure 2

Optical properties for the applied materials LS-6943 and Sylgard 184, (a) Refractive indices, (b) Transmission spectra.

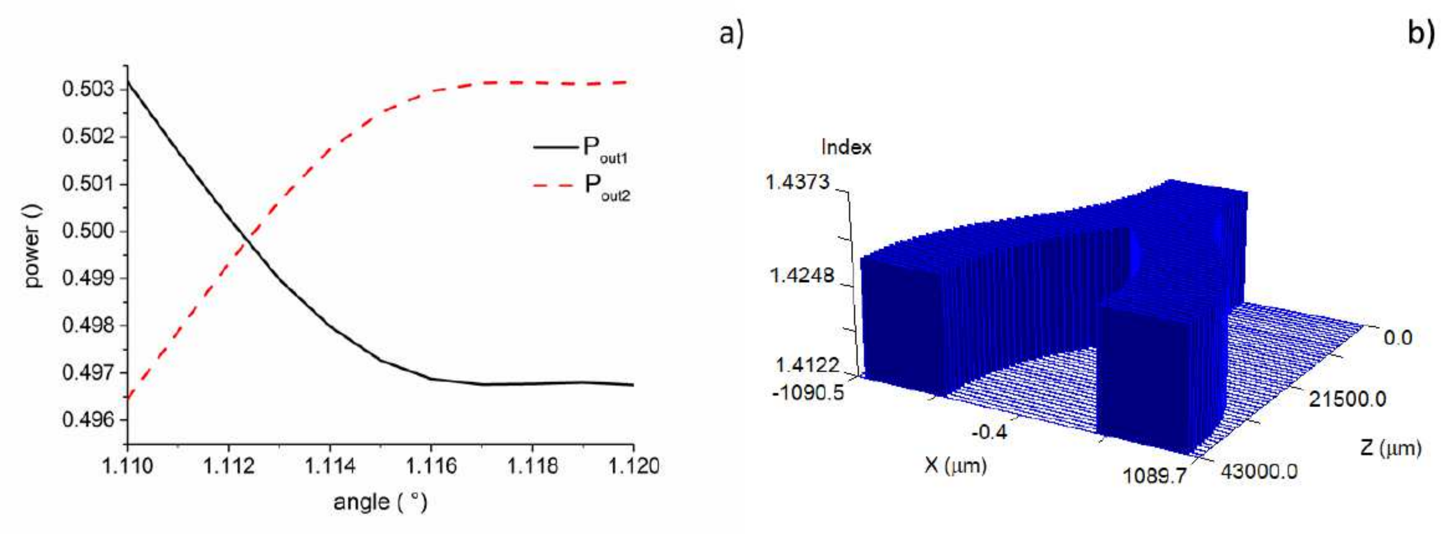

Figure 3

(a) Dependence of the outputs Pout1 and Pout2 normalized optical power to the branching angle Ω, (b) Refractive index profile for the optimized dimensions 1x2Y Sylgard 184/LS-6943.

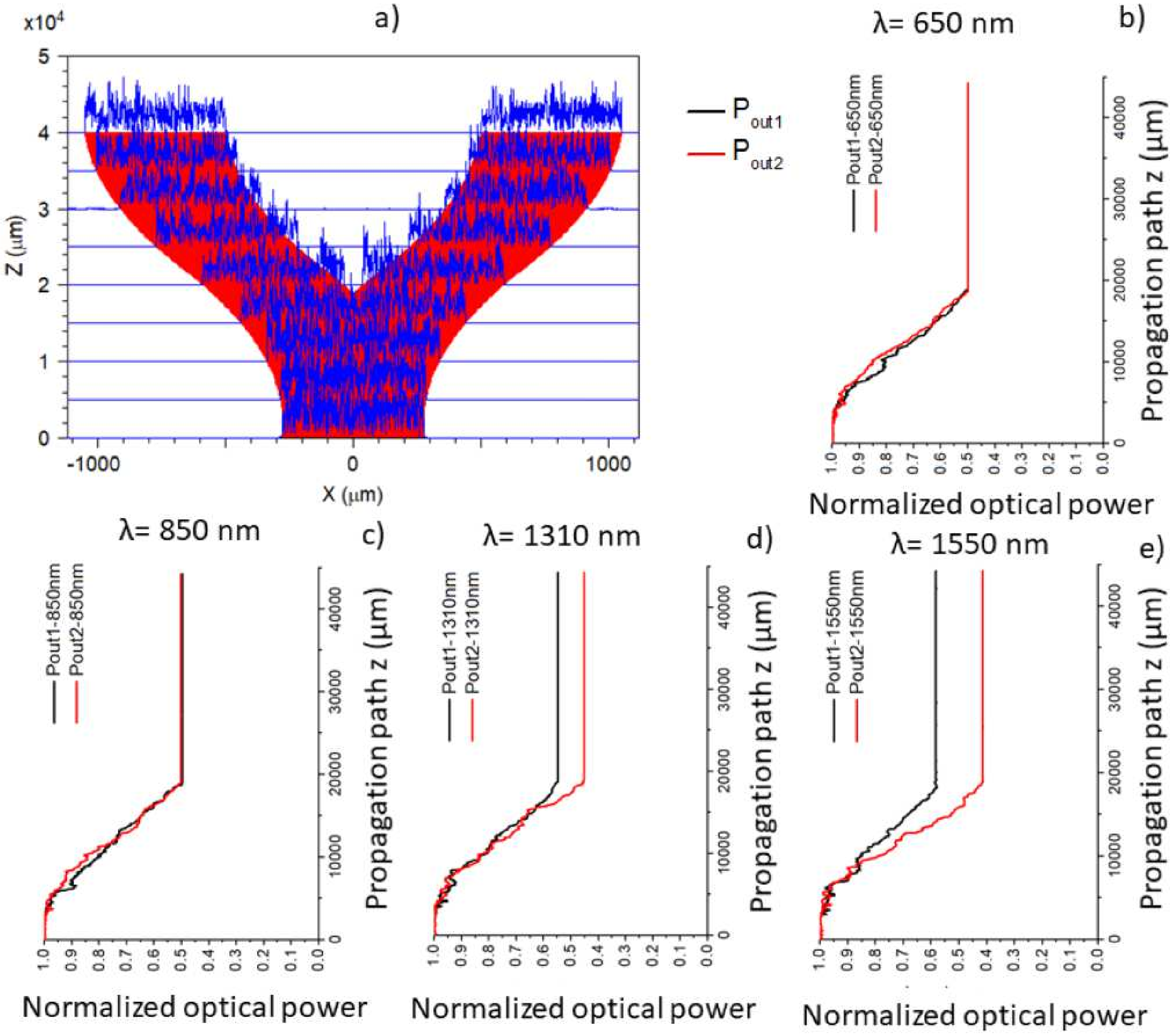

Figure 4

Normalized optical signal propagation of the optimized 1x2 Y splitter, (a) graphical display of the signal propagation and signal propagation for wavelengths (b) 650 nm (nf= 1.4277, ns= 1.4109), (c) 850 nm (nf= 1.4229, ns=1.4068), (d) 1300 nm (nf= 1.4186, ns=1.4029), (e) 1550 nm (nf= 1.4173, ns=1.4017).

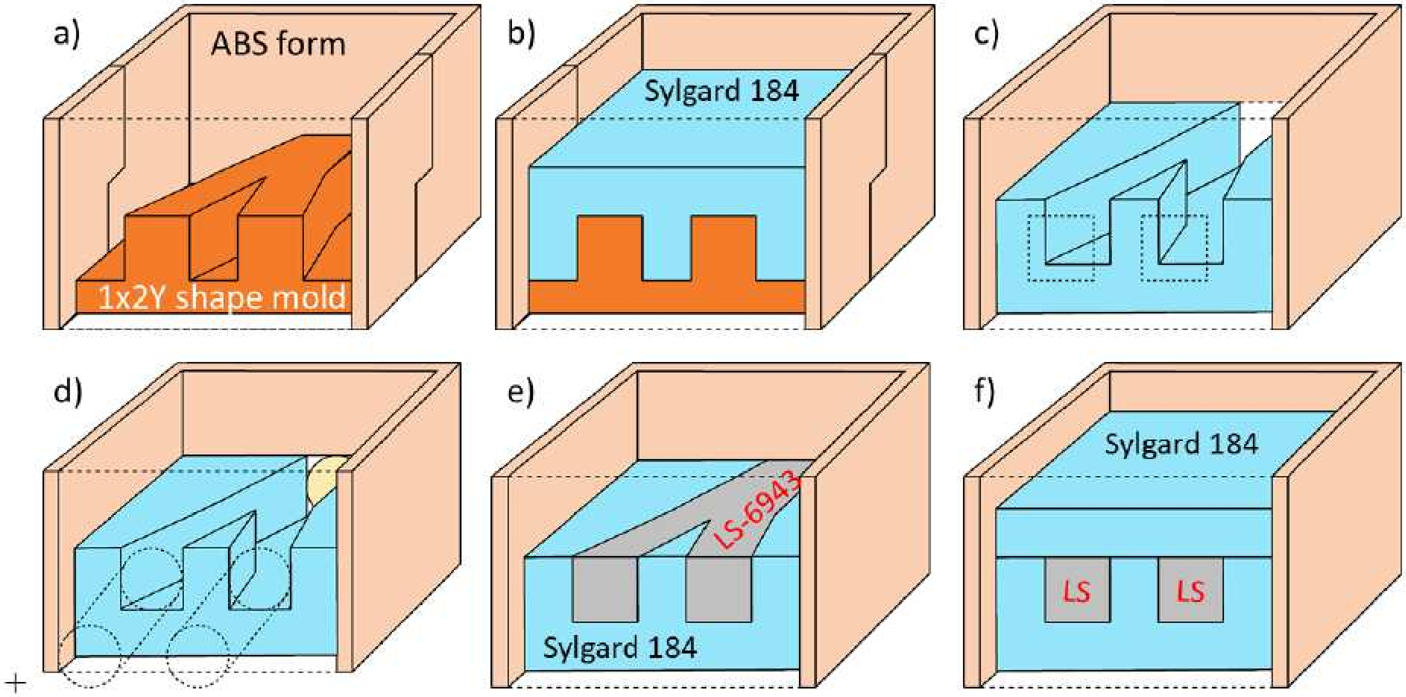

Figure 5

Fabrication process for the optical splitters, (a) negative epoxy mold with required pattern inserted in ABS form, (b) negative mold poured with PDMS Sylgard 184 elastomer – fabrication of the substrate, (c) separation of the PDMS substrate with 1x2Y shape from the mold, turn upside down and insertion into ABS form, (d) assembling input and output fibers, (e) filling up the core LS-6943 elastomer layer in PDMS U-groove, (f) filling up Sylgard 184 PDMS cover layer.

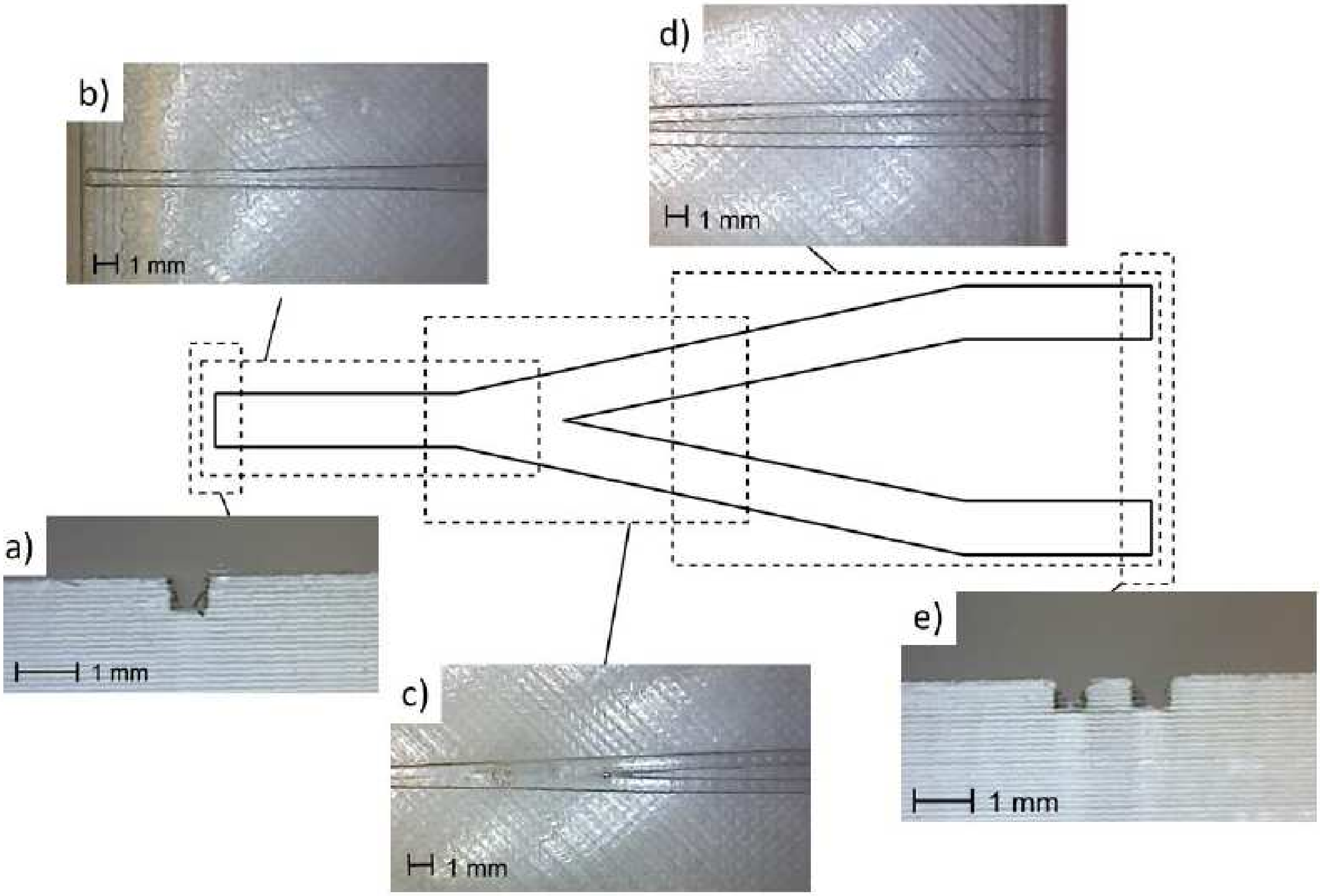

Figure 6

Detailed image of 1x2Y Sylgard 184 substrate prepared of the assembling one input, two outputs fibers and pouring LS-6943 elastomer core layer. (a) input cross-section view, top view of the (b) input part, (c) taper region with two output waveguides, (d) two output waveguides, (e) cross-section view of the two outputs waveguides.

Figure 7

Image of the fabricated 1x2Y splitter in 3D-printed ABS form.