Design of optical polymer planar multimode power 1x2 and 1x3 splitter for POF waveguide

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Abstract. *This article deals with design, construction and diagnostics of polymer multimode splitters with optical power division rate of 1:2Y and 1:3Y. The dimensions of the splitters were optimized for connecting standard plastic optical fibres with 1 mm diameter of core and cladding. Geometrical dimensions of optical splitters 1:2Y were at first designed according to Mr. Bertrami's model. Design of those structures was then optimized using the optical beam propagation method (BPM) in the BeamPROP™ software by Rsoft Design Group. Based on experience obtained during the 1:2Y structure design were created 1:3Y optical splitter designs. Deposition tests have been carried out based on those designs. Those tests led to fabrication of several selected structures. Norland Optical Adhesive polymer were used as waveguide layers and polymethyl methacrylate (PMMA) or polydimethylsiloxane (Sylgard) were used as substrate and cover layer. This paper also shown measurement methods used for diagnostics of realized structures. The conclusion of this publication discusses the most significant results.*

Keywords

Optical Planar Waveguides, Splitter, Polymer, Large Core, BPM Method

1. Introduction

Optical power branching splitters are passive key components used for distribution and processing of optical signals. The simplest optical branching splitter is Y-junction with one input and two output ports [1, 2]. The conventional symmetrical Y-junctions have even number of output waveguides. As realizations of similar devices are usually done by linking two-branch waveguides the number of the output ports increases the dimensions of such splitters. Branching splitters with non-symmetrical output distribution of optical power [1] and those with odd number of output waveguides with symmetrical optical power distribution [1] have been described as well. In a conventional three-branch splitter with a uniform index distribution most of the power is concentrated in central branch. Up to now only few papers dealing with realization of three-branch planar splitters with symmetrical power distribution have been presented [1].

Principle of one of them [3] is based on a conventional structure with a central branch as a triangularly shaped spacing area. This area has lower refractive index than that of the waveguides and its function is to reduce the transmission coefficient between the main waveguide and the central branch (see Fig.1a). Other options design of optical 1x3 splitter are shown in the Fig. 1b) – 1f).

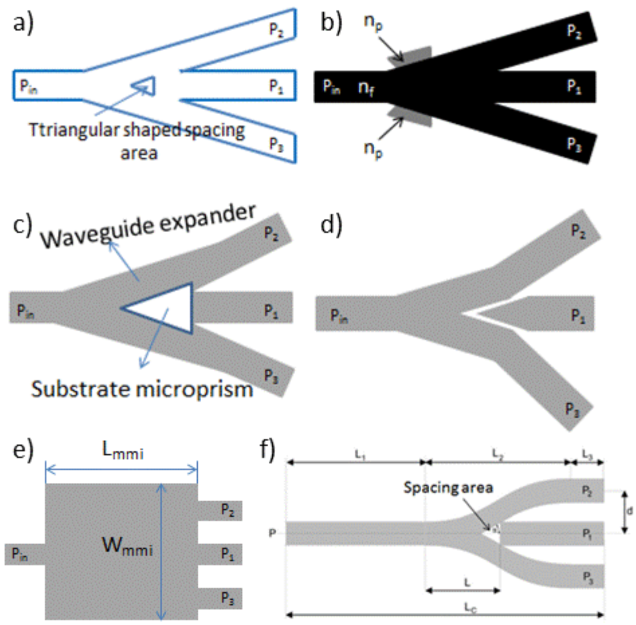

Fig. 1. Schematic view of the published 1x3 splitters [4]: a) splitter with a triangular shaped spacing area [3], b) splitter with microprisms [4], c) splitter using substrate microprisms and waveguide expanders [5], d) fork-type splitter [6], e) splitter using multimode interference [7, 8], f) the proposed 1x3Y splitters with triangular shaped spacing [4, 9].

2. Modelling of the Large Core 1x3Y Power Splitters

The design was done by beam propagation method (BPM) with help of BeamPROP program in the frame of the specialized simulation package MOST, (RSoft's, Multi-Variable Optimization and Scanning Tool) for acrylic-based polymer used as a waveguide core material and poly(methyl methacrylate - PMMA) as a substrate and cover layer. The substrate can also be used Gardasil or Makrolon AR (see Tab. 1). On the input optical splitters is one plastic optical fiber and at the output of two (three) plastic optical fiber (POF). Dimensions of the rectangular waveguide were set so that it could be connected to a standard plastic optical fiber (POF) with core diameter 980 μm and 20 μm thick cladding layer [4].

Optical waveguide structure used for designing the optical splitter is the step-index rectangular waveguide consisting of a waveguide core layer of refractive index (n_f), surrounded in all sides by materials having refractive index (n_c) lower than that of a core waveguide (see Fig. 2).

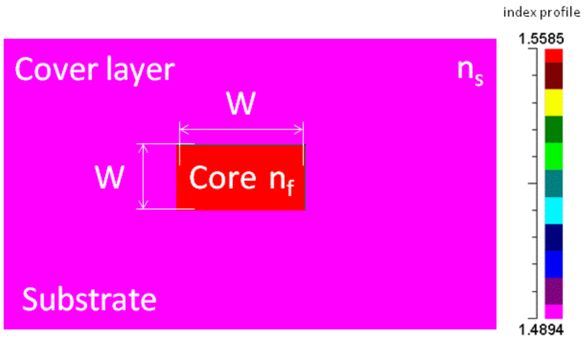

Fig. 2. Cross-sectional view of the proposed large core optical rectangular waveguide.

One of the goals of this work was to try to find a material substrate, which has a lower refractive index than the PMMA, due to reduction of the geometric dimensions of the resultant structure was due to the higher refractive index difference between the substrate and the waveguide layer. I managed to get the material Makrolon and Sylgard. Before the design was due to make a best possible simulations measured the refractive indices of the materials used for the substrate and the waveguide layer using a device Metricon [4, 10].

Refractive index measurement was performed at five wavelengths and it 473 nm, 632.8 nm, 964 nm, 1311 nm and 1552 nm. Measurement results for the substrates are shown in Fig. 3 and the waveguide layers of Fig. 4. From these values and the graph was drawn from him, then OriginPro 8.0 program subtracted values for the wavelengths 532 nm, 650 nm, 850 nm, 1310 nm and 1550 nm. The readings for the substrates are shown in Tab. 1 and Tab. 2 shows the values for the waveguide layer [10].

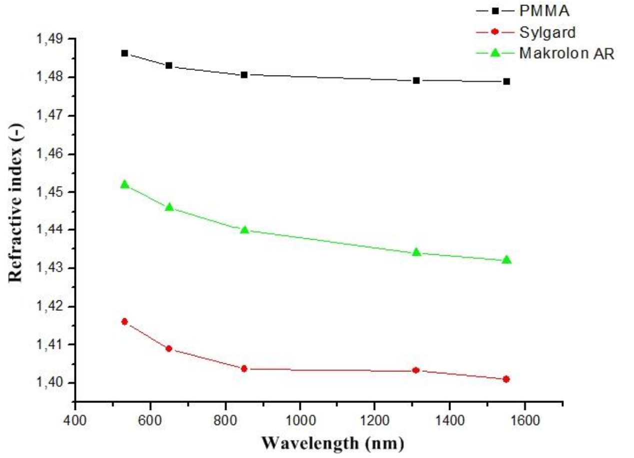

Fig. 3. The measured values of the refractive index for the materials used in the device substrates with Metricon [10].

λ (nm)	Refractive Index ns (-)		
	PMMA	Sylgard	Makrolon AR
532	1.495	1.416	1.452
650	1.489	1.409	1.446
850	1.485	1.407	1.440
1310	1.479	1.403	1.434
1550	1.478	1.401	1.432

Tab. 1. The values of the refractive indices of the materials washers deducted from the graph in Fig. 3 [10].

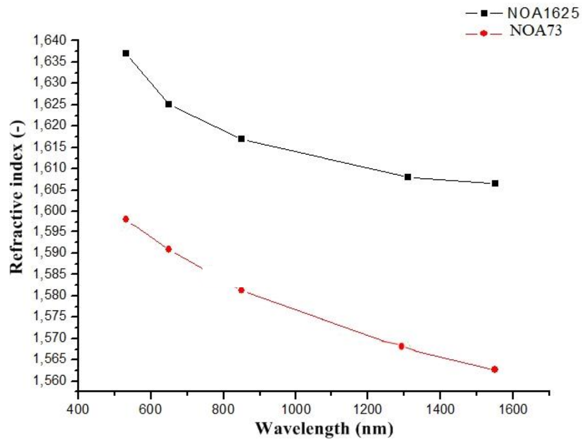

Fig. 4. Measured values of the refractive index of the materials used for the waveguide layers using equipment Metricon [10].

λ (nm)	Refractive Index n_f (-)		
	NOA1625	NOA73	ENR
532	1.637	1.564	1.602
650	1.625	1.558	1.591
850	1.617	1.550	1.582
1310	1.608	1.545	1.574
1550	1.606	1.539	1.572

Tab. 2. The values of the refractive indices of the waveguide layer used to design structures subtracted from Fig.4 [10].

Suitability of the polymer materials proposed for the cores of the planar waveguides was checked by measuring of their transmission spectra by UV-VIS-NIR Spectrometer Shimadzu. This measurement showed that NOA materials were transparent within the range from 400 nm to 1600 nm.

I started with designing of optical splitters with two output waveguides and prosecuted to three output splitters. Geometrical dimensions of the two-output splitters were calculated by analysis for a lossless Y-junction published by Beltrami. And then I intended to extend the design to a three-output variety. To achieve it I had to widen the distance (gap) between two original output waveguides to insert the third central waveguide, as connecting three large core output fiber waveguides needs its space. For all my designed structures we used PMMA substrates and core waveguide layers NOA [4, 10].

3. Design of structure multimode planar waveguide

Before the computer simulation program BeamProp I made the proposal 1x2Y splitters model, which published Mr. D. Bertrem [1]. For the design of 1x2 Y splitters I like polymer substrate used Polymethylmethacrylate (PMMA). As a waveguide layer used different kinds of polymers NOA (Norland Optical Adhesive). Proposed structure of the optical splitters 1x2Y is shown in Fig. 5, where Fig. 5a) is marked transverse structure and Fig. 5b) shows the parameters that are important to the theoretical calculations of the structure and on which is based the equation 1 to 3.

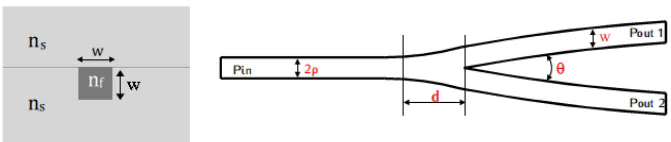

Fig. 5. a) the transverse structure b) structure splitters 1x2Y [11].

Maximum angle θ (see Fig. 3) between the two output waveguides beaded S-shaped, and the left of the channel waveguide Pout 1 and right of the channel waveguide Pout 2, can be expressed [9, 10]:

$$\theta \le \sin^{-1}\left\{\frac{\sqrt{n_f^{\,2}-n_s^{\,2}}}{n_f}\right\} \quad , \qquad (1)$$

where *nf* is the refractive index of the waveguide layer and *ns* is the refractive index of the substrate. Minimum length d (Fig. 3), taperovaného the channel waveguide can be determined by equation [9, 10]:

$$d = \frac{d\cdot\sin\Omega}{\rho\cdot(2-\cos\Omega)} \quad , \qquad (2)$$

where w is the width of the waveguide layer, ρ = w / 2, D is a standardized length, which has the value 1, and Ω is the angle described by [9, 10]:

$$\Omega \le \frac{\theta\cdot D}{D+1} \qquad (3)$$

Theoretical calculations for the PMMA substrate and different types of waveguide layers I performed for the wavelengths 532 nm (green light), 650nm (red light) and 850 nm to indicate the influence of wavelength variations on the given parameters. The actual simulation of various types of splitters but I just performed for a wavelength of 650 nm. Examples of calculated parameters of optical structures PMMA / PMMA NOA1625 and / NOA73 are shown in Tables 3 and 4.

λ (nm)	Refractive index (-)		Parameters Splitters		
	PMMA n_s	NOA1625 n_f	Θ(rad/⁰) ≤	Ω (rad/⁰)≥	d (mm) ≥
532	1,495	1.637	0.42/24°2.4‘	0.21/12°1.8‘	2.45
650	1,489	1.625	0.41/23°36.6‘	0.205/11°4‘	2,51
850	1,485	1.617	0.406/23°18.6‘	0.203/11°8‘	2,53

Tab. 3. The parameters for the structure of optical splitters PMMA/NOA1625 1x2Y [10].

λ (nm)	Refractive index (-)		Parameters Splitters		
	PMMA n_s	NOA73 n_f	Θ (rad/⁰) ≤	Ω (rad/⁰)≥	d (mm)≥
532	1.495	1.564	0.30/17°8‘	0.15/8° 5.4‘	3.38
650	1.489	1.558	0.294/16°2‘	0.147/8°25.2‘	3.45
850	1.485	1.550	0.290/16°39‘	0.145/8°18.6‘	3.49

Tab. 4. The parameters for the structure of optical splitters PMMA / NOA73 1x2Y [10].

For example, for comparison of the structure of Tab 3, wherein the structure is formed from a substrate of a polymer PMMA with a value of refractive index of 1.489 for a wavelength of 650 nm and the waveguide layer with the polymer NOA1625 with a refractive index of 1.625 for the same waveguide length and Table 4, where u structure used as a substrate and again PMMA waveguide layer NOA73 polymer with refractive index 1.558 again. The theoretical length d (see Fig. 5) tapered the channel waveguide structure is in PMMA / NOA1625 2.51 mm and with the structure of PMMA / NOA73 value due to the lower refractive index difference between the substrate and the waveguide layer increased to 3.45 mm.

4. Design multimode 1x2Y splitters and 1x3Y splitters without and with Rectangle Shape Spacing

I started with designing of optical splitters with two output waveguides and prosecuted to three output splitters. Geometrical dimensions of the two-output splitters were calculated by analysis for a lossless Y-junction published by Beltrami [23] and then we intended to extend the design to a three-output variety. To achieve it we had to widen the distance (gap) between two original output waveguides to insert the third central waveguide, as connecting three large core output fiber waveguides needs its space. For all our designed structures we used PMMA substrates and waveguide layers polymer NOA. Dimensions of the rectangular waveguide were set so that it could be connected to a standard plastic optical fiber (POF) with core diameter 980 μm and 20 μm thick cladding layer [10].

4.1 Design multimode power 1x2Y splitter

Fig. 6 is shown the topological diagram of a planar multimode optical splitters with a splitting ratio of 1x2. The proposed planar multimode splitters are formed by the input waveguide via the passage (Pin) with the waveguide layer. Waveguide layer in this case is formed from a polymer type NOA. The waveguide layer is applied to the Y-groove in the substrate from the polymer PMMA. Input a channel waveguide (PIN) is via wallpapering a channel waveguide (2) (polymer NOA), which extends in the direction of propagation of the optical signal, opens into the left output of the channel waveguide (Pout 1) and the right output of the channel waveguide (Pout 2) in the S-shaped waveguide structure is applied to the upper covering layer, which is always formed by the same material from which the substrate is designed, in my case of PMMA [10].

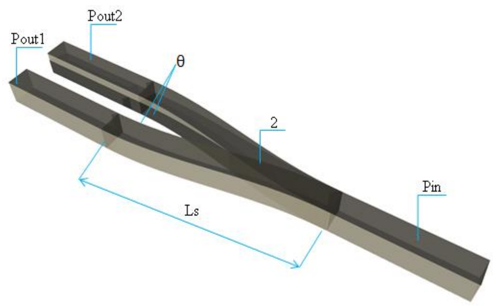

Fig. 6. Structure of multimode splitters 1x2Y with marked parameters [10].

After calculating critical parameters based on the model p. Beltrami, I've done modeling optimum dimensions splitters using BeamProp™ from RSoft Design. Optimizing the dimensions of the optical splitters I have done using the bundled MOST, which is part of the program BeamProp™.

In the Fig. 7 is the proposed Structure PMMA/NOA1625 and in the Fig. 8 is ratio course output.

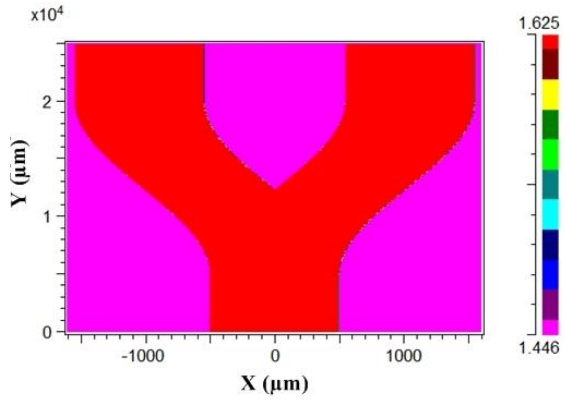

Fig. 7. Results of simulation of the 1x2Y splitter with photopolymer NOA1625 waveguide layer for 650 nm, computed index profile (top view) [10].

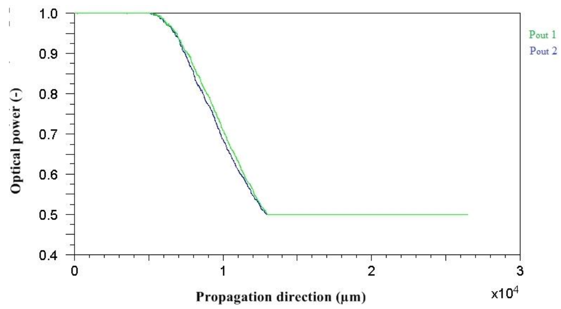

Fig. 8. Results of simulation of the 1x2Y splitter with photopolymer NOA1625 waveguide layer for 650 nm, normalized optical signal propagation [10].

Green line designated as Pout and one blue line Pout 2 correspond to the optical signal, which according to Fig. 6 spreads the input waveguide via the passage (PIN), which is filled waveguide layer of polymer NOA1625. The signal then propagates through tapered a channel waveguide (2) which extends in the direction of propagation of the optical signal, and a gap left in the output of the channel waveguide (Pout 1) and the right output of the channel waveguide (Pout 2) having the shape of S. The ratio of output power for optimized wavelength of 650 nm was 50.06 : 49.94% [10].

4.2 Design multimode power 1x3Y splitter

As was shown in previous chapters, normally in the three-branch optical splitter with a uniform refractive index distribution the most of the optical power will be predominantly driven via the central branch. To provide more proportional distribution of the power we proposed an optical splitter with inserted rectangle shaped spacing area between the input and the central output branch. This rectangle is made from same materials (PMMA) as the surrounding core materials. Our design also aimed to optimize the dimension of the rectangle shaped spacing and to find the optimal position for this to achieve proportional 1x3Y powers splitting. For that optimization we again used BPM simulation for operating wavelength of 650 nm (using MOST) [10].

After designing optical splitters with two output waveguides I suggested symmetrical splitters with three output waveguides (Fig.9).

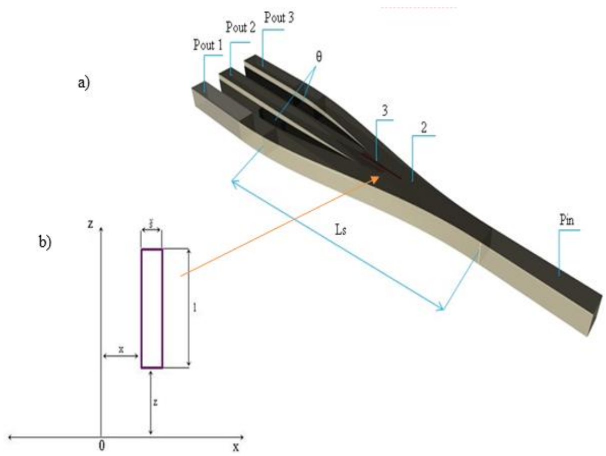

Fig. 9. a) Structure symmetrical optical splitters with three output waveguides 1x3Y b) detail of a rectangular region which ensures uniform distribution of optical power [10].

The proposed planar multimode optical POF splitters (see Fig. 5a) with a dividing ratio 1x3Y is constituted waveguide structure, which consists of an input of the channel waveguide (PIN), which is formed waveguide layer of various types of polymer NOA. The waveguide layer is applied to the Y-groove which is formed in a substrate of a polymer PMMA. Input a channel waveguide is then over tapered a channel waveguide (2) formed waveguide layer extends in the direction of the optical signal to the left output of the channel waveguide (Pout 1) having S-shape middle-direct the output of the channel waveguide (Pout 2) and right output the channel waveguide (Pout 3), which is again shaped S. All of these output the channel waveguides are formed by the same waveguide layer [10].

In this structure, which divides the optical output power into three branches, is in addition to tapered the channel waveguide (2) is inserted in the direction of propagation of the optical signal rectangular area 3 (see detail in Fig. 9b), which has the same refractive index, which has designed substrate structure. This region thus has a lower refractive index than the refractive index of the channel waveguide tapered (2) of the completed waveguide layer. In order to symmetrical distribution of the output optical signal to all three output of channel waveguides must be inserted rectangular area (3) located in a precisely defined location in taperované portion. Location of embedded rectangular area must be such that the electromagnetic field distribution at the end tapered the channel waveguide (2), where the signal is divided into three output of channel waveguides symmetrical. The end of the rectangular area (3) is disposed in a plane crossing tapered the channel waveguide (2) to direct the output of the channel waveguide (Pout 2). This intermediate rectangular area (3) with respect to the longitudinal axis of the direct output of the channel waveguide (Pout 2) misaligned depending on the electromagnetic field distribution of optical modes in the waveguide structure. The dimensions and exact location of the rectangular area (3) thus depends on the working wavelength to which the structure will work also depends on the refractive index of the substrate, the refractive index of the waveguide layer and the geometry proposed by the waveguide structure. Because the solution of this problem is very complicated and cannot be the location and size of the rectangular area (3) determined by calculation, it is necessary to design the structure to use specialized software, in my case BeamPROP^{TM} software, which uses the method for calculating BPM **[**10].

The optimized structure is proposed in Fig. 6. Fig. 10 indicates the distribution of the refractive index of the proposed structure viewed from above, where the value of 1.489 is the refractive index of the substrate and the cover layer of a polymer PMMA and 1.625 is the refractive index of the waveguide layer formed from a polymer NOA1625 for waveguide length of 650 nm. Fig 11 is stated propagation of the optical signal structure for waveguide length λ = 650 nm [10].

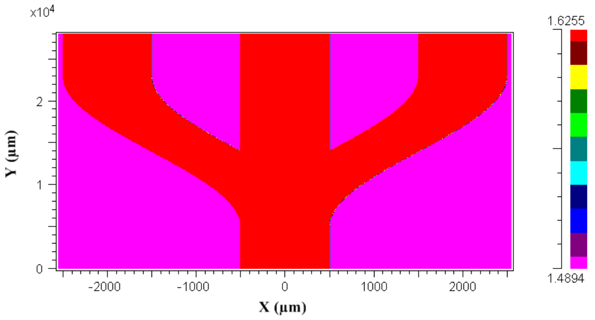

Fig. 10. Results of simulation of the 1x3Y splitter with photopolymer NOA1625 waveguide layer for 650 nm, computed index profile (top view) [10].

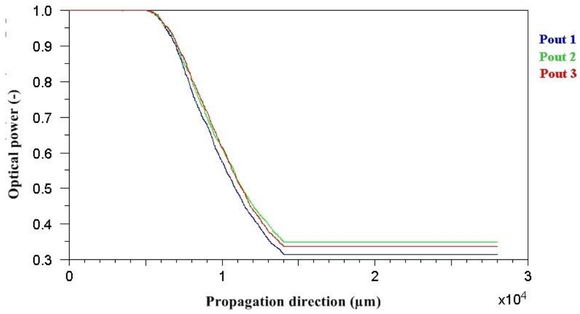

Fig. 11. Results of simulation of the 1x3Y splitter with photopolymer NOA1625 waveguide layer for 650 nm, normalized optical signal propagation [10].

From Fig. 11 show that without the rectangular area is the distribution of the output optical power unbalanced and the output optical power is split in a ratio of 33.9: 32.9: 33.2. The middle branch output Pout 2 thus has a significantly higher output (34.9%) compared to the output Pout 1, wherein the optical output power reaches a value (31.4%) and the output Pout 3, an output power of 33.7%. Pout 1 is compared to the best theoretical value of optical power (33.3%) differ by 4.8% [10].

The structure of Figure 12 has the same geometrical dimensions as the previous structure of PMMA / NOA1625 without a rectangular area. The only change here is the insertion of the rectangular area, which ensures symmetrical distribution of the output optical power output in all three of channel waveguides. The length l embedded rectangular area of 2800 µm (see Figure 9 b)) and its width W is 66.6 µm. The location is then 120 µm from the z-axis (parameter x) at a distance of 10 000 µm from the x axis (a parameter). Proposed optimized structure is shown in Fig 12. In the Fig. 12) indicates the distribution of the refractive index of the proposed structure viewed from above, where the value of 1.488 is the refractive index of substrate and the cover layer of a polymer PMMA and 1625 is the value of the refractive index of the waveguide layer formed from a polymer NOA1625 for waveguide length of 650 nm. In Fig. 13 indicates propagation of the optical signal structure for the wavelength λ = 650 nm [10].

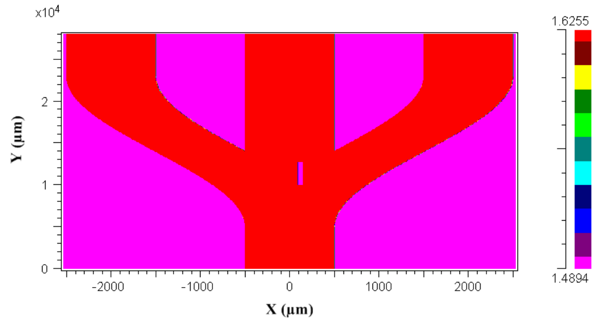

Fig. 12. Results of simulation of the 1x3Y splitter with photopolymer NOA1625 waveguide layer for 650 nm, computed index profile (top view) [10].

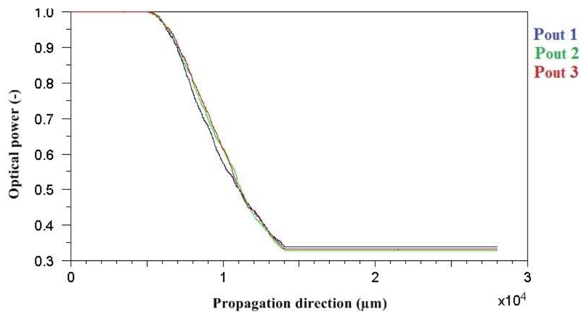

Fig. 13. Results of simulation of the 1x3Y splitter with photopolymer NOA1625 waveguide layer for 650 nm, normalized optical signal propagation [10].

The ratio of the output power is compared to the structure in which was inserted a rectangular area, divided fairly symmetrically, in a ratio of 33.9: 32.9: 33.2. Since the best theoretical value (33.3%) was the worst output branch Pout 1 differs by 1.8%.

5. Fabrication

Fabrication process of the designed optical splitters is step by step shown in Fig. 14.

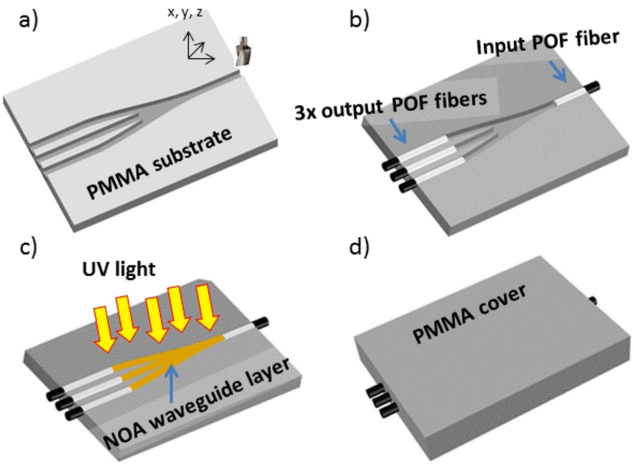

Fig. 14 Fabrication process for the optical splitters, a) CNC machining into polymer substrate, b) inserting of standard POF waveguide, c) filling up taper region with core layer and applying UV curing process, d) assembling top cover layer [4].

The Y-groove for the waveguide core layer into PMMA substrate was made by using CNC NONCO Kx3 milling machine (milling tool size of 0.8 mm, spindle 1800 rpm/min and moving 36 mm/min (see Fig. 14a). Then I inserted standard POF waveguides (PFU-UD1001-22V (which were to serve as the input/output waveguides) into the groove (see Fig. 14b). Next I filled up the taper region with NOA polymer and applied UV curing process (see Fig. 14c). Finally, top cover PMMA is placed onto the structures (see Fig. 14d) [4].

6. Measurements and Results

Properties of the splitters were checked using optical microscope and the measurement revealed that it had good optical quality and dimension of the fabricated structure corresponded well with the size of the proposed splitters what concerns dimension of input/outputs waveguides, taper region, central and S band waveguides.

Fig. 15a show detail NOA waveguide layer for optical splitter 1x3Y. Fig. 15b shows the final structure with the core waveguide layer, assembling input/output waveguides and a top protection layer.

Fig. 15. Images of PMMA substrate with 1x3 Y-groove, a) detail NOA waveguide layer b) detail of the splitter with waveguide layer and assembled input/output POF waveguide 1x3Y splitter [10].

Fig. 16 shows in a simple visual way how the final three-branch optical power splitter with the rectangle shaped spacing (having assembled POF input and output waveguides and NOA core waveguide layer and cover PMMA layer) transmits the optical light. To demonstrate it, we used the laser tester FLS-240 operating at 635 nm.

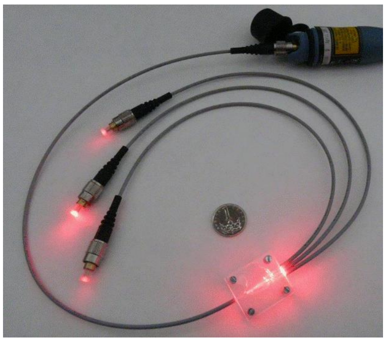

Fig. 16. Images of 1x3Y splitters transmitting optical signal 635 nm [4].

The schema of the insertion optical loss measurement is given in Fig. 17. The measurements were done for green light (532 nm, Nd:YVO_4 laser), red light (650 nm, laser Safibra OFLS-5 FP-650) and for 850 nm (laser Safibra OFLS-5 DFB-850).The outputs lights were measured by optical powermeter Thorlabs PM200 with silicon detector S151C (the accuracy of the set-up to be ±5%).

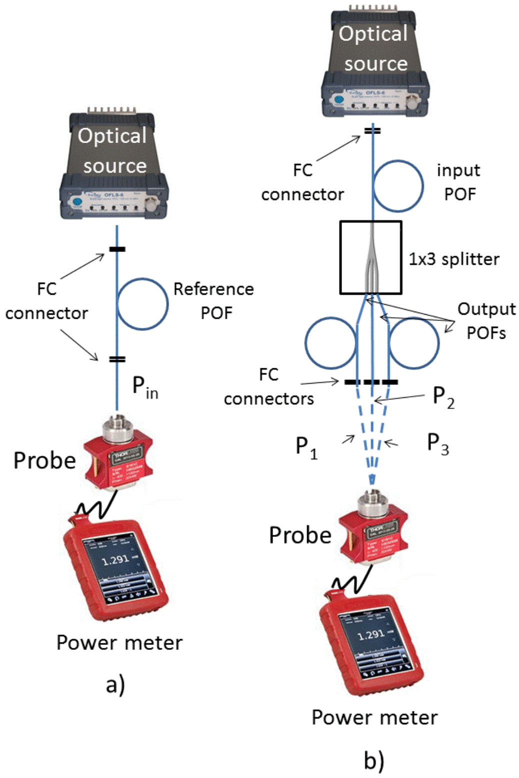

Fig. 17. Set up for insertion optical loss measurement (see text above) [4].

Selected structures of optical splitters I measured the output power from which I subsequently determined according to the relationship 1 Insertion Loss structures:

$$L = -10 \cdot \log \frac{P_1 + P_2 + P_3}{P_{in}} \text{ (dB)}, \qquad (4)$$

where P_{in} means optical power after transmition through the reference fiber POF and P_1 and P_2 and P_3 are outgoing optical powers. The obtained data for the samples are summarized in Tab. 5.

When I first joined the measurements between optical radiation source and optical power meter reference fiber of the same length as the length of the sample splitters, including input and output fibers, and I measured the performance of the reference fiber (Pin see equation 1 – Fig. 17a). Then I joined the measured sample, particularly where I measured power output branches left and right branches output (Pout 1 and 2) – Fig. 17b [4].

Sample	Waveguide layer / Coupling ratio (%)	Insertion losses (dB)		
		532 nm	650 nm	850 nm
131 (1x3Y)*	NOA88 / 12:75:13	4.37	3.61	2.81
133 (1x3Y)*	NOA73 / 29:57:14	4.82	6.2	5.38
137 (1x3Y)	NOA88 / 9:58:33	6.64	5.93	4.11
85 (1x2Y)*	NOA1625 / 72:28	2.46	4.01	4.28
89A (1x2Y)*	NO1625 / 65:35	2.84	5.54	4.92

* reference samples without insertion of rectangle shape spacing

Tab. 5. Insertion optical losses of the 1x3Y and 1x2Y splitters.

Best value attenuation was reached for the sample with the substrate and the waveguide layer PMMA NOA1625 (the Smple. 85*). At 532 nm was measured the value of attenuation of 2.46 db. At 650 nm wavelength was measured with the sample value of the attenuation of 4.01 db. At 850 nm wavelength, the sample had an optical attenuation of 4.28 db. The value of embedded optical loss is mainly influenced by the waveguide layer coating technology. The ratio of the output optical power could affect connectivity POF fiber splitters at the output, because the fiber could be wrong and could have deployed it harder to navigate the structure of optical radiation.

In the optical splitters with three input waveguides failed to achieve that the optical output power distributed symmetrically. And for this reason, the failure to optimize production structures 1x3Y having in its rectangular shape an embedded rectangular area guaranteeing this symmetry. The result could be to improve the production of additional deposition tests, especially the optimization of production intermediate rectangular portion. However, as the results expected from the simulation were more optimistic, we believe that there are still some possibilities to improve the real structures by solving technical parameters of the fabrication.

Comparing the simulation of optical multimode 1x3Y splitters without a rectangular section, where the output power divided in a ratio of 33.9 (P1): 32.9(P2): 33.2(P3) (right branch: central branch: left branch), and simulation optical multimode 1x3Y splitters with embedded rectangular shape (33.9(P1): 32.9(P2): 33, 2(P3)) and the ratio of output power varies significantly. These simulation results, unfortunately, has not yet been practically verified because the best distribution of optical power in the structure with an inserted rectangular shape were measured for a sample of 133 *, which is the ratio of output power 29:57:14.

7. Conclusion

I designed, realized and measured properties of multimode polymer 1x2Y and 1x3Y power splitters. The design was done by beam propagation method using RSoft software. For the splitters we used NOA 1625, NOA73 and NOA88 core waveguide layers and substrate and cover protection layers were made of PMMA. The designed structures were then realized by CNC engraving and the waveguiding pattern was hardened by the UV radiation.

The measurement of optical insertion loss proved that the PMMA/NOA73 1x3Y splitter had the lowest insertion loss 2.42 dB at 532 nm, optical loss of the PMMA/NOA88 splitter was 2.81 dB at 850 nm and optical loss of the PMMA/NOA1625 splitter was 2.46 at 532 nm.

Both, simulation and realization of the splitters showed the important role of insertion a rectangle into the central waveguiding region. The results of the simulations, however, shows, that there are still some reserves in the technological procedures that may make the parameters of the real structures even better.

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