Large Core Planar 1 x 2 Optical Power Splitter with Acrylate and Epoxy Resin Waveguides on Polydimetylsiloxane Substrate

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Abstract. *Fabrication process of multimode 1 x 2 optical rectangular planar power splitter suitable for low-cost short distance optical network is presented. The splitters were designed by beam propagation method for standard input/output plastic optical fibre. Materials used for the splitter were: UV acrylate photopolymer polymer or epoxy resin for optical core waveguide layers and Y-groove substrate for the core layer was poly(methyl methacrylate) or polydimetylsiloxane made by replication process on poly(methyl methacrylate) pattern. The insertion losses of 1x2 splitters with acrylate waveguide layers were around 2.7 dB at 532 nm and 4.1 dB at 650 nm and those for epoxy resin waveguide layer were around 3.7 dB at 850 nm. The 1x2 splitters were tested by signal transmission being connected to the internet network by using optoelectronic switches and we achieved the maximum possible transmission data rate as provided by the computer network.*

Keywords

Multimode splitter, large core, optical planar waveguide, polymer, beam propagation method.

1. Introduction

Communications technology and facilities advanced rapidly in the last decades because of growing popularity of the internet entertainment and development of data communications. Data traffic has been growing much faster than 10% per year and to keep that trend it would require expansion of capacity of global telecommunications networks [1], [2]. Great progress has been also reported in the development of short-length networks such as in-home, office [3], [4], next generation aircraft and in automotive optical communications and data transmission systems [5]. Optical data communication using optical fiber as the transmission medium is the only solution to handle the massive growth of telecom and datacom traffic. Single mode silica optical fibers are currently used for long haul backbone optical communication systems while copper wires still dominate data transmission to the desktop and in-homes. Copper wires are compatible with existing equipment and are cheaper than silicon fibers for transmitting the signal over short distance, but to transmit 10-Gbit Ethernet for more than 15 m special high performance copper wires are still needed [2]. Therefore, to achieve higher transmition speeds for longer distances, it is highly desirable to replace copper wires by optical fibers. Nowadays, in short-haul systems Plastic Optical Fibers (POF) are commonly used. Plastic/Organic waveguides have suitable properties for the desired applications due to a great potential for their high transparency from visible to infra red wavelengths, well-controlled refractive indices, reasonable temporal and temperature stability and low optical losses [6-11]. Last but not least, plastic photonics structures are also environment-friendly materials and can be fabricated by easier fabrication processes compared to photonics structures made from semiconductors, glass or optical crystals materials.

To develop new photonics structures for such short-haul POF systems is strongly required. Y-splitters are one of the key components for signal processing and signal routing. The Y-splitter waveguides are used for distributing signals from one port to two (or more) output ports. The reported polymer Y-dividers were aimed mostly for single mode operation [12-16], and it means that the core sizes of the reported Y-dividers had to be approximately hundreds of nanometers to few micrometers depending on the core and substrate materials and on the thought operation wavelength. Multimode Y-splitters with core sizes smaller than 200 μm and 100 μm were also reported [17], [18]. In the last decade we are witnessing an effort to develop large core (around 1000 μm) POF optical power splitters [19-24] and it seems that for that purpose polymer materials are the right choice.

We have already reported [25] about properties of the multimode polymer 1x2 splitters designed by ray tracing method. The cores of our waveguide-forming splitter were made of Norland Optical Adhesives (NOA 73 and NOA 88) and two types of polymers, poly(methyl methacrylate) (PMMA) or poly(methyl-methacry limide) (PMMI) were used for the substrates and cover layers. Our best samples had insertion optical losses around 3.5 dB at 532 nm. We also reported on design and properties of the multimode 1x2 and 1x4 Y optical power planar splitters made of the new core polymer waveguides Norland Optical Adhesives (NOA1625) and with PMMA substrate used as substrates and cover layers [26], [27]. The measurement of optical insertion losses proved that the 1x2 splitter had optical losses 2.7 dB at 532 nm, 4.1 dB at 650 nm and 4.5 dB at 850 nm. The 1x4 splitter had optical losses 14.7 dB at 532 nm, 17.6 dB at 650 nm.

In this paper we are going to focus on the design and fabrication of large core polymer planar optical 1x2 splitter with acrylate or epoxy resin waveguide layers and polydimetylsiloxane substrate. Polydimetylsiloxane (PDMS) substrate if compared to poly(methyl methacrylate) (PMMA) substrate, which was used previously for realization of the planar splitters, has much lower value of the refractive index and thus it may be suitable for realization of a splitter with more compact dimensions.

2. Design of the Large Core Power Splitters

2.1 Design of the Multimode Splitter

Optical waveguide structure used for designing optical splitter is the step-index rectangular waveguide, and the typical thin-film waveguide structure consists of three dielectric regions, namely a substrate (n_s), a waveguide core (n_f) and a cover (n_c) layer (Fig. 1).

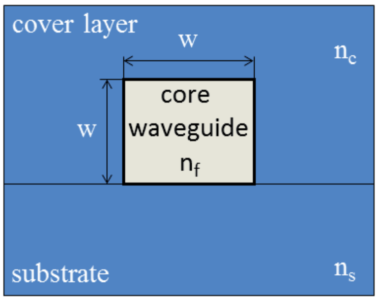

Fig. 1. Cross-sectional view of the proposed large core optical rectangular waveguide.

The refractive index of the guiding layer n_f must be higher than the refractive indices of the substrate n_s and the cover layer n_c:

$$n_f > n_s \ , \ n_f > n_c \ . \tag{1}$$

In our case we used the optical waveguides that were based on the same materials for substrate and cover protection layer ($n_c = n_s$) for all the designed splitters.

Here we are going to report on designing optical polymer splitters with two types of acrylate waveguide layer (Norland Optical Adhesive – NOA1625 and NOA73) and one epoxy resin (Epoxy Novolac Resin - ENR) core waveguide layers. The designs were done for two types of the substrates and cover protection layers – poly (methyl methacrylate) (PMMA) and polydimetylsiloxane (PDMS) and width of the waveguide core (w) was 1 mm.

The design started with calculation of the dimensions of the tapered part d and complementary critical angle θ of the splitter; calculation was based on analysis for a lossless Y-junction published by Beltrami [28] and applied for the designing of a splitter with a large waveguide core by Ehsan [29]. The geometrical structure of the designed optical planar multimode 1x2 splitter is shown in Fig. 2.

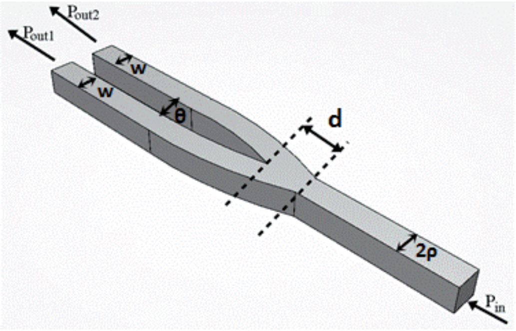

Fig. 2. Geometrical structure of the proposed symmetric 1 x 2 Y optical power splitter.

Beltrami showed [28] that for a lossless Y-splitter the branching angle Ω must obey:

$$\Omega \le \frac{\theta \cdot D}{D+1} \tag{2}$$

where θ is the complementary critical angle, given by the following relationship:

$$\theta \le \sin^{-1}\left\{\frac{\sqrt{n_f{}^2 - n_s{}^2}}{n_f}\right\} \tag{3}$$

D is the normalized value and it is defined by the relationship:

$$D = \frac{d \cdot \sin\Omega}{\rho \cdot (2 - \cos\Omega)} \tag{4}$$

where d is the waveguide taper length and ρ is the waveguide half-width (w = 2ρ).

We also calculated the relative index difference Δ (5) and value of numerical aperture NA (6).

$$\Delta = \frac{n_f^2 - n_s^2}{2 \cdot n_f^2} \ . \tag{5}$$

NA is a dimensionless number that characterizes the range of angles over which the optical waveguide structures can accept light:

$$NA = \sqrt{n_f^2 - n_s^2} \ . \tag{6}$$

Before the actual proposal and modeling of the splitters we measured refractive indices of the waveguides NOA, ENR layers and PMMA, PDMS substrates. Refractive indices were measured by dark mode spectroscopy [30] using Metricon 2010 prism-coupler system for five wavelengths 473 nm, 632.8 nm, 964 nm, 1311 nm and 1552 nm [31]. The obtained results are shown in Fig. 3. The highest refractive index value of the waveguiding materials was found with the acrylate NOA1625 while NOA73 was found to have the lowest one. The PDMS substrate had significantly lower refractive index than PMMA.

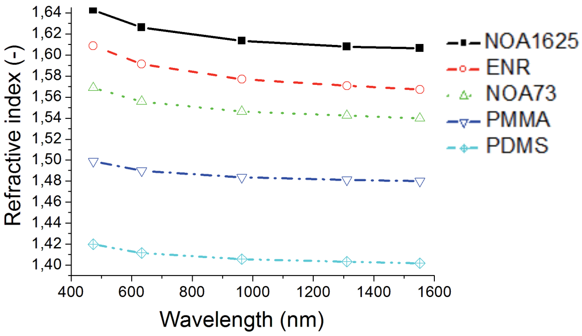

Fig. 3. Refractive indices of NOA1625, ENR, NOA73, ENR waveguide layers and PMMA, PDMS substrates measured by dark mode spectroscopy.

Calculation data of geometrical dimensions of the designed splitters for PMMA/NOA1625 structure are summarized in Tab. 1 and calculation of geometrical dimensions of the designed PDMS/NOA73 and PDMS/ENR structures are summarized in Tab. 2 and in Tab. 3.

PMMA/NOA1625							
λ (nm)	n_s (-)	n_f (-)	Δ (-)	θ (°)	Ω (°)	d (mm)	NA (-)
532	1.495	1.636	0.082	23.96	11.98	2.46	0.66
650	1.489	1.625	0.080	23.61	11.82	2.50	0.65
850	1.485	1.618	0.079	23.39	11.70	2.52	0.64

Tab. 1. Refractive indices and calculated dimensions of the optical splitters on PMMA substrate/cover layer and NOA1625 core waveguide.

PDMS/NOA73							
λ (nm)	n_s (-)	n_f (-)	Δ (-)	θ (°)	Ω (°)	d (mm)	NA (-)
532	1.416	1.564	0.090	25.13	12.56	2.35	0.66
650	1.410	1.555	0.089	24.94	12.47	2.37	0.65
850	1.407	1.550	0.088	24.80	12.40	2.38	0.65

Tab. 2. Refractive indices and calculated dimensions of the optical splitters on PDMS substrate/cover layer and NOA73 core waveguide.

PDMS/ENR							
λ (nm)	n_s (-)	n_f (-)	Δ (-)	θ (°)	Ω (°)	d (mm)	NA (-)
532	1.416	1.602	0.109	27.88	13.94	2.14	0.75
650	1.410	1.591	0.107	27.60	13.80	2.16	0.74
850	1.407	1.582	0.105	27.20	13.60	2.18	0.72

Tab. 3. Refractive indices and calculated dimensions of the optical splitters on PDMS substrate/cover layer and epoxy resin ENR core waveguide.

From the data in the tables it follows that the smallest dimensions of the splitters could be achieved by using the materials with a large relative refractive index difference Δ.

2.2 Design of 1x2 Y Splitter on PMMA Substrate

After calculating the dimensions of the optical splitters by Beltrami analysis the dimensions of the splitters were more precisely specified by BeamPROP^{TM} software that uses finite difference beam propagation method (BPM). We applied 2D dimensional channel with multimode source operating at 650 nm.

The first step was to optimize the dimensions for optical splitter made of acrylate NOA1625 core layer and PMMA substrate. Schematic view of the cross-section is shown in Fig. 4.

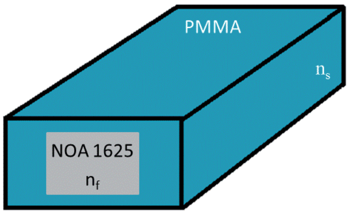

Fig. 4. Schematic view of the cross-section of the multimode optical waveguide for photopolymer NOA1625 core layer, PMMA substrate and cover protection layer.

The results of the simulations for the optimized structure that had the best parameters are shown in Fig. 5.

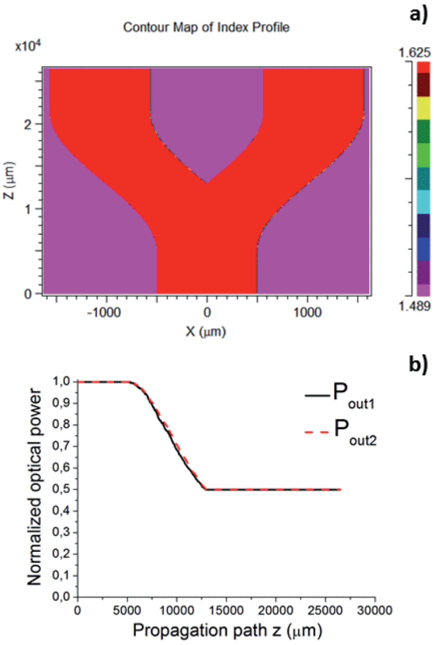

Fig. 5. Results of simulation of the optimized 1x2 Y POF splitter with photopolymer NOA1625 waveguide layer and PMMA substrate for 650 nm, a) the top view computed index profile, b) normalized optical signal propagation showing that the signal from both branches totally overlaps each other.

Fig. 5a shows a top view of the computed refractive index profile of the optimized structure with the pertinent dimensions. Fig. 5b shows that the input signal is really symmetrically divided into two branches each of them having exactly the same power, so that they overlap. Modeling was done for the wavelength of 650 nm and for refractive index of the waveguide NOA layer 1.625 and that of PMMA substrate 1.489.

2.3 Design of the 1x2 Y Splitter on PDMS Substrate

After designing the 1x2 splitter with PMMA substrate we started to design a structure of the 1x2 splitter on PDMS substrate and cover protection layer with acrylate photopolymer NOA73 or epoxy resin ENR waveguide layers. The schematic view of the cross-section of such structures is shown in Fig. 6.

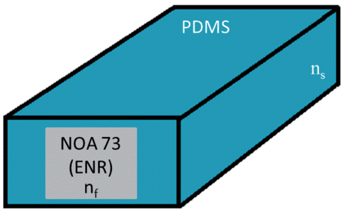

Fig. 6. Schematic view of the cross-section for the multimode optical waveguide with photopolymer NOA73 and epoxy resin ENR core layer, PDMS substrate and cover protection layer.

The results of the simulations for the optimized structure that had the best parameters for photopolymer NOA73 core waveguide are shown in Fig. 7 and those for epoxy resin ENR core waveguide are shown in Fig. 8.

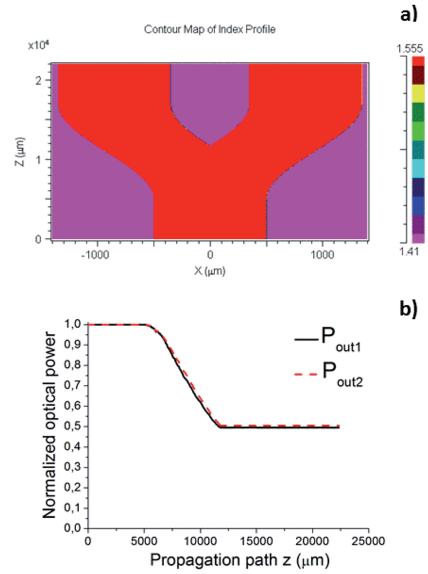

Fig. 7. Results of simulation of the optimized 1x2 Y POF splitter with photopolymer NOA73 waveguide layer and PDMS substrate for 650 nm, a) the top view computed index profile, b) normalized optical signal propagation showing that the signal from both branches totally overlaps each other.

Fig. 7a shows a top view of the computed refractive index profile of the optimized structure PDMS/NOA73 with the pertinent dimensions while in Fig. 7b there are two overlapping curves of optical power of both branches, which again means that they are perfectly symmetrical. Modeling was done for the wavelength of 650 nm and for the refractive indices of the waveguide NOA73 layer and PDMS substrate 1.555 and 1.410, resp.

Fig. 8a shows a top view refractive index profile of the optimized PDMS/ENR structure and Fig. 8b shows propagation of the signal at the wavelength of 650 nm for refractive index of the waveguide ENR layer 1.591 and for that of the PDMS substrate 1.410; again the signals of both branches are perfectly symmetrical, similarly as in previous cases (see Figs. 5b and 7b).

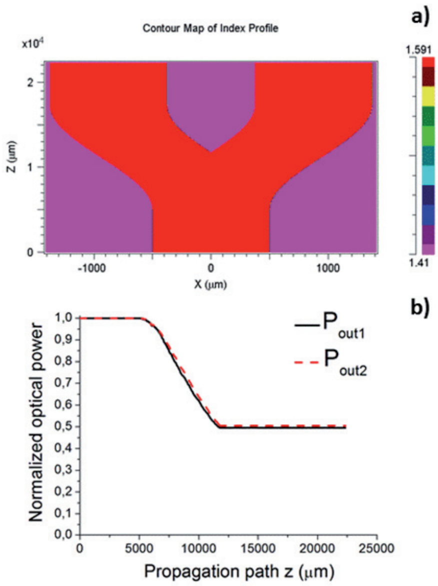

Fig. 8. Results of simulation of the optimized 1x2 Y POF splitter with epoxy resin (ENR) waveguide layer and PDMS substrate for 650 nm, a) the top view computed index profile, b) normalized optical signal propagation showing that the signal from both branches totally overlaps each other.

3. Fabrication of the Splitters

Fabrication process of the structure shown in Fig. 4 has been already described in our papers [25], [26]. Different fabrication process was applied for our newly designed optical splitters with photopolymer or epoxy resin core waveguide layers with PDMS substrate and cover protection layer and it is shown step by step in Fig. 9.

The first step was making the PMMA pattern of the Y-groove by CNC NONCO Kx3 milling (Fig. 9a). After that the negative master made of polyuretan resin PU 501LR hardened with PH27 was cast into the PMMA pattern (Fig. 9b). Then the polydimethylsiloxane (PDMS) was inlaid into the PU 501 negative master (Fig. 9c). The next step of the process was assembling of the input and output standard POF waveguides (Fig. 9d) and filling up the taper region with core polymer waveguide with consequent UV-irradiation (Fig. 9e). Finally, the top PDMS cover was deposited onto the structure (Fig. 9f).

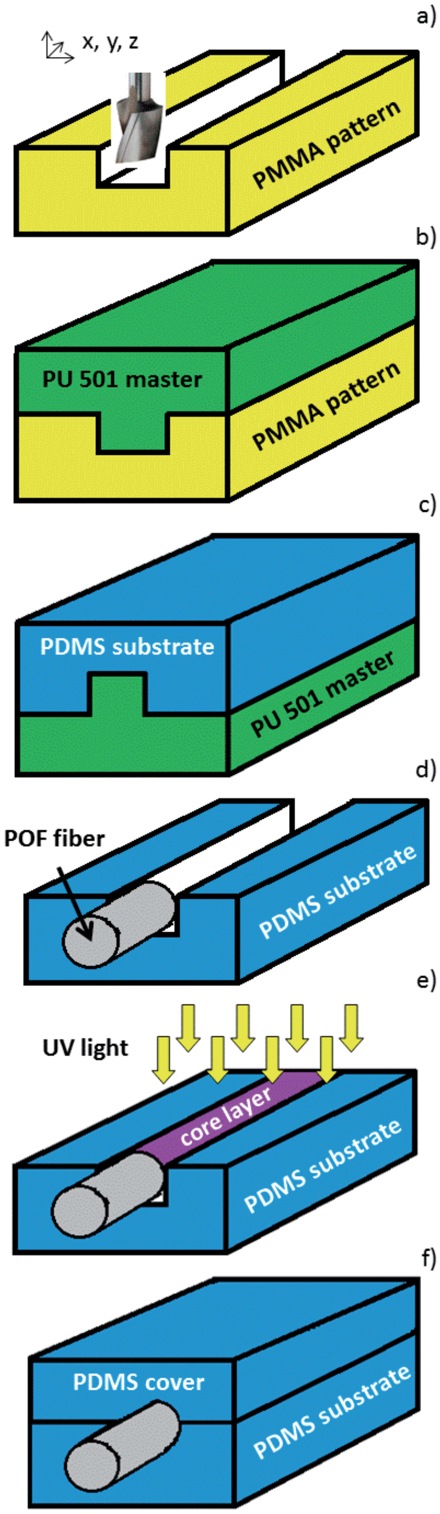

Fig. 9. Fabrication process of the waveguide, which will be a base for our optical splitters, a) fabrication of the PMMA pattern by using CNC machining, b) fabrication of negative PU 501 master, c) fabrication of the Y-grove from PDMS, d) assembling input/output POF waveguides, e) filling up taper region with core waveguide layer and applying UV curing process, f) assembling top cover layer.

4. Experimental Setup and Results

Properties of the PMMA pattern, negative motives of the Y-groove as well as the splitters were checked with optical microscope. Fabricated Y-groove by CNC into the PMMA substrate to make PMMA/NOA1625 structure is shown in Fig. 10a. Practical realization of the PDMS splitters is illustrated in Figs.10b-d, where shape of the Y PMMA pattern is shown in Fig. 10b, negative PU 501 LR/PH 27 master is shown in Fig. 10c and, finally, shape of the PDMS Y-grove substrate is given in Fig. 10d.

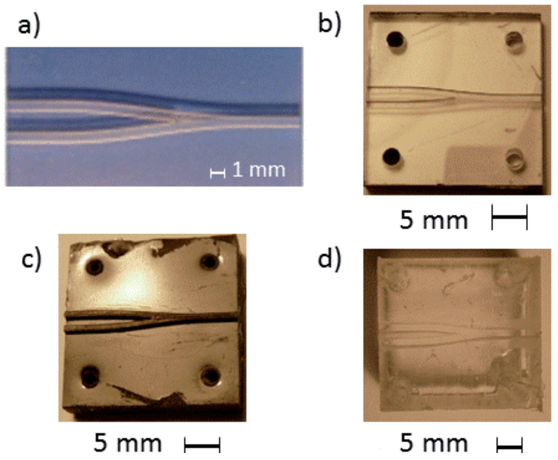

Fig. 10. Images of the a) Y-groove PMMA substrate for the PMMA/NOA1625 splitter, b) PMMA pattern for PDMS splitter, c) negative PU 501 LR/PH 27 master, d) final Y-groove PDMS substrate.

Fig. 11 shows final splitters with assembled standard POF (PFU-UD1001-22V) input and output waveguides transmitting signal from FLS-240 laser at 635 nm; Fig. 11a shows PMMA/NOA1625 structure with POF fiber with standard optical FC/PC connectors, and Fig. 11b shows PDMS/ENR structure assembling with POF fibers with demountable bare fiber adapter optical connectors. The figure shows that the signal is divided into two output branches.

Insertion optical loss measurements were done for green light (532.8 nm, optical source Nd:YVO$_4$ laser), for red light (650 nm, laser Safibra OFLS-5 FP-650) and for 850 nm (laser Safibra OFLS-5 DFB-850). The output lights from the structures were measured by optical powermeter Thorlabs PM200 with silica detector S151C. The schema of the measurement method is given in Fig. 12. The measurement started with determining the optical power (P_{out}) coming from the source and passing through the reference 30 cm long POF fiber (Fig. 12a) and then the power was measured separately for the left (P_{out1}) and right (P_{out2}) output branches of the splitter (Fig. 12b). Both fibers are 15 cm long.

Now the insertion optical losses were calculated from (6) and the obtained data are summarized in Tab. 4.

$$L = -10 \cdot \log \frac{P_{out1} + P_{out2}}{P_{in}} . \tag{7}$$

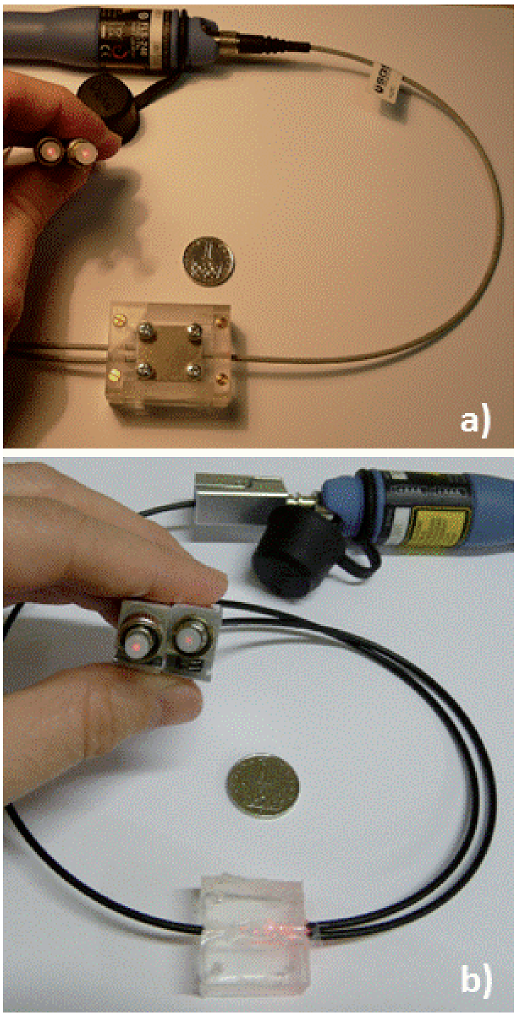

Fig. 11. Images of splitters transmitting optical signal (λ = 635 nm), a) PMMA/NOA1625 structure, b) PDMS/ENR structure.

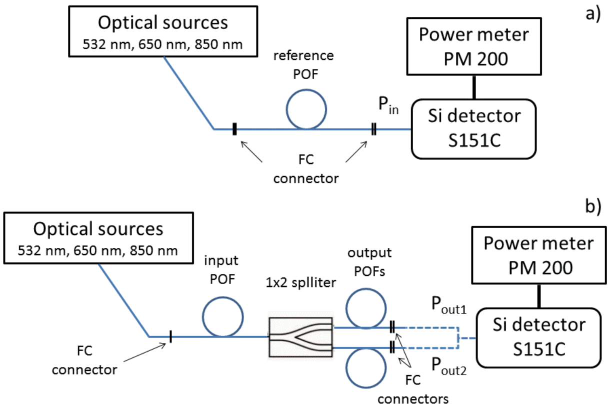

Fig. 12. Set up for insertion optical loss measurement (see text above).

The measurement of optical insertion losses proved that 1x2 PMMA/NOA1625 Y splitter had optical losses 2.7 dB at 532 nm, 4.1 dB at 650 nm and 4.5 dB at 850 nm. Optical losses of the 1x2 PDMS/NOA73 Y splitter were 4.3 dB at 650 nm while the 1x2 PDMS/ENR Y splitter had optical losses 5.0 dB at 650 nm and 3.7 dB at 850 nm.

splitter	insertion losses (dB)		
	532 nm	650 nm	850 nm
PMMA/NOA1625	2.7	4.1	4.5
PDMS/NOA73	4.9	4.3	4.0
PDMS/ENR	10.7	5.0	3.7

Tab. 4. Insertion optical losses of the splitters.

The realized 1x2 splitters were tested for the quality of transmission of the signal. This was done by connection to internet network and using two optoelectronic switches KCD-303P-A2 (KTI Networks) and we achieved the maximum possible transmission data rate, provided by the computer network 100 Mb/s.

5. Conclusion

We designed, realized and measured optical properties of multimode polymer planar 1x2 splitters with POF input/output fibers. The dimensions of the splitters were set by Beltrami analysis and then more precisely specified by modeling, which was done using beam propagation method (BeamPROP^{TM} from RSoft software).

The calculations based on Bertrami's analysis and resulting data given in Tabs.1 to 3 show that the bigger the difference between the refractive indices of the substrate and pertinent waveguiding layer the smaller the dimensions of the proposed 1x2 Y structures. However, more detailed analysis using BPM method farther revealed that when the output planar waveguides are to be connected to the standard POF waveguides then the gap between the output waveguides has to be sufficiently big to enable assembling such a structure. It means that for practical realizations one must find a compromise between the big difference of the relative refractive indices and critical waveguide taper length *d*.

For the splitters, we used acrylate photopolymer or epoxy resin core waveguide layers and poly(methyl methacrylate) or polydimetylsiloxane materials were used for substrate and cover protection layer. The Y-grooves for fiber input/output waveguides from PMMA substrates were realized by CNC engraving. The Y-groove for fiber input/output waveguides from PDMS substrate was realized by using PMMA pattern and polyuretan resin PU 501 master negative Y motive. The photopolymer core waveguiding acrylate or epoxy resin core layer was then filled into Y-groove and UV hardened.

The measurement of optical insertion loss proved that the PMMA/NOA1625 had the lowest insertion loss 2.7 dB at 532 nm; and optical loss of the PDMS/ENR splitter was 3.7 dB at 850 nm.

As to our opinion, the easy fabrication process and suitable properties make these splitters attractive for applications in low cost short distances optical networks.

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