Design, Fabrication and Properties of the Multimode Polymer Planar 1 x 2 Y Optical Splitter

Václav PRAJZLER [1], Ngoc Kien PHAM [1], Jarmila ŠPIRKOVÁ [2]

[1] Dept. of Microelectronics, Czech Technical University, Technická 2, 168 27 Prague, Czech Republic
[2] Institute of Chemical Technology, Technická 5, 166 27 Prague, Czech Republic

xprajzlv@feld.cvut.cz, jarmila.spirkova@vscht.cz

Abstract. *We report about design, fabrication and measurement of the properties of multimode 1 x 2 optical planar power splitter. The splitters were designed with help of OptiCAD® software using ray tracing method. The dimensions of the splitters were then optimized for connecting standard Plastic Optical Fiber. Norland Optical Adhesives glues were used as optical waveguide layers and the design structures were completed by CNC engraving on Poly(methyl methacrylate) or Poly(methylmethacrylimide) substrate. The devices have the insertion loss around 7.6 dB at 650 nm and the coupling ratio was 52:48.*

Keywords

Multimode 1x2 splitter, optical planar waveguide, polymer, ray tracing.

1. Introduction

Today the most important media for transmitting data are electrical lines, radio and optical fibers. Electrical lines are limited by the skin effect. The special feature of radio is that all users within a cell have to share capacity of the transmission. Extremely complicated behavior of the channel, which is a consequence of the multi-path propagation and resulting interferences, as well due to disturbance coming from external sources, has to be compensated by adaptive procedures. Compared with electrical lines and radio, optical systems offer much bigger capacity without any disturbance.

While single mode optical fibers are currently used for long haul optical communication systems, multimode waveguides can be used for short-distance applications. Polymer waveguides with large core diameter (around 1 mm) are utilized in short-distance communication for applications such as in automobile networks, private office and home networks. Due to the rapid widespread of the internet communication in the Fiber-to-the-Home (FTTH), automotive industry new photonics structures are strongly required [1].

Y-splitters belong to the most important optical passive structures. Y-splitter waveguides are used for distributing signals from one port to two (or more) output ports. In recent years, construction of a divider has been reported in various papers [2-6] but the core sizes of the reported Y-dividers were mostly smaller than 100 μm [7]. Only a small number of the published papers described a planar optical splitter for multimode fiber with core diameters around 1000 μm. The first paper dealing with 1000 μm splitter was published by Takezawa in 1993 [8] and similar coupler was lately presented by the Institute for Microtechnology Mainz in 2003 [9]. Other attempts to produce Plastic Optical Fiber (POF) splitters were presented also by Mizuno from the University of Sendai in 2005 and 2006 [7], [10]. One of the last papers, which described planar multimode splitters, was published by Ehsan from the Institute of Microengineering and Nanoelectronics [11-13] and the last one by Park, coming from Honam Research Center, Electronics and Telecommunications Research Institute, appeared in 2011 [14].

In this paper we report about design and properties of the multimode 1x2 Y optical power planar splitters made of polymer waveguides. Our proposal is based on the design described in [11] and it is constructed for input and output standard POF waveguides.

2. Design of Multimode Optical Splitters

The splitters were proposed by using ray tracing method. The structures were drawn in CAD Creo elements/pro 5.0 software and then the modeling was done by using OptiCAD® version 10.050. The structure of the designed optical planar waveguide is shown in Fig. 1.

We used two types of the UV photopolymer supported by Norland Optical Adhesives glues as optical waveguide layers (NOA73, NOA88) and two types of the substrates and cover layers made of Poly(methyl methacrylate) (PMMA) supplied by Goodfellow Cambridge Ltd. or Poly(methylmethacry-limide) (PMMI) supplied by Evonik Industries AG.

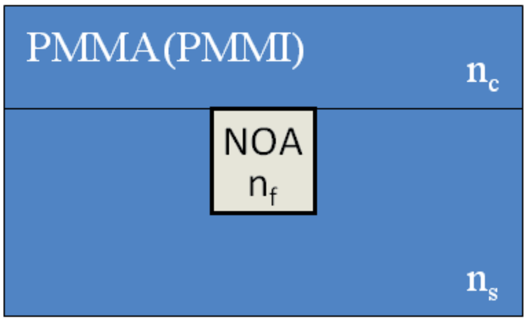

Fig. 1. Schematic view on the multimode optical waveguide cross-section ($n_c = n_s$).

Before the modeling we calculated geometrical dimensions of the splitter by analyzing what would give optimum waveguide taper length d (see Fig. 2) published by Beltrami [15]. It was shown that for a lossless Y-splitter, the branching angle Ω was specified as:

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

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

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

n_f is the refractive index of the core waveguide material and n_s is the refractive index of the cladding material. D is the normalized value and it is defined by the relationship:

$$D = \frac{d \cdot \sin\Omega}{\rho \cdot (2 - \cos\Omega)} \tag{3}$$

where d is the waveguide taper length and ρ is the waveguide half-diameter ($\omega = 2\rho$) [13], [15]. The geometrical structure of the designed optical multimode coupler is shown in Fig. 2.

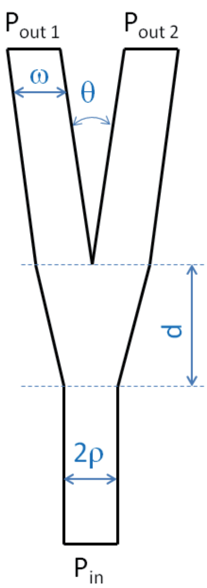

Fig. 2. Geometrical structure of the designed optical splitter.

We also calculated dimensionless waveguide frequency [9]:

$$V = \frac{2 \cdot \pi}{\lambda} \cdot \frac{\omega}{2} \cdot \sqrt{n_f^{\,2} - n_s^{\,2}} = \frac{\pi \cdot \omega}{\lambda} \cdot NA \tag{4}$$

where λ is the operating wavelength, ω is the width of the waveguide and NA is numerical aperture. The justification of using ray models is that the relationship given below is valid:

$$V >> 1. \tag{5}$$

Before the actual proposal and modeling the waveguide layer NOA73 and NOA88 were deposited on silicon substrate and the resulting refractive indices were measured by optical ellipsometry. We also measured refractive indices of the PMMA and PMMI substrates. The obtained data (Fig. 3) were then used for calculation of geometrical dimension of the designed splitters (see Tab. 1.).

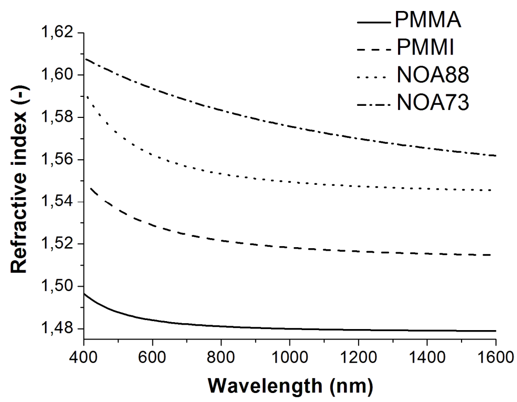

Fig. 3. Refractive indices of PMMA, PMMI, NOA polymers measured by ellipsometry.

λ (nm)	Substrate n_s (-)		Core n_f (-)	
	PMMA	PMMI	NOA73	NOA88
532	1.4683	1.5335	1.5981	1.5686
650	1.4830	1.5264	1.5908	1.5592
850	1.4807	1.5205	1.5813	1.5521

Tab. 1. Refractive indices of the layers obtained by ellipsometry that were used for design of the optical splitters.

In Tab. 2 and 3, the parameters for the structure of PMMA/NOA73 and for the structure of PMMI/NOA88 are given, respectively.

PMMA/NOA73					
λ (nm)	θ (°)	Ω (°)	d (mm)	NA (-)	V (-)
532	21.56	10.78	2.72	0.59	$6.1 \cdot 10^6$
650	21.21	10.61	2.76	0.58	$4.9 \cdot 10^6$
850	20.55	10.27	2.85	0.56	$3.7 \cdot 10^6$

Tab. 2. Calculated dimensions of the optical splitters on PMMA substrate and with NOA73 core waveguide.

After calculating the dimensions of optical splitters the modeling was performed using ray tracing method by Opticad software and the schematic view of the 3D model

PMMI/NOA88					
λ (nm)	θ (°)	Ω (°)	d (mm)	NA (-)	V (-)
532	12.14	6.07	4.75	0.33	$5.7\cdot10^6$
650	11.77	5.89	4.90	0.32	$4.6\cdot10^6$
850	11.58	5.79	4.98	0.31	$3.5\cdot10^6$

Tab. 3. Calculated dimensions of the optical splitters on PMMI substrate and with NOA88 core waveguide.

of the designed splitter is illustrated in Fig. 4a while Fig. 4b shows how the rays are scattered from the optical source through the designed and optimized structure of the splitter to the output waveguides. The figure also shows the rays that are not guided within the waveguiding layer but they are faded away into the substrate. In order to get the most accurate simulation but acceptable length of the process we used 106 rays.

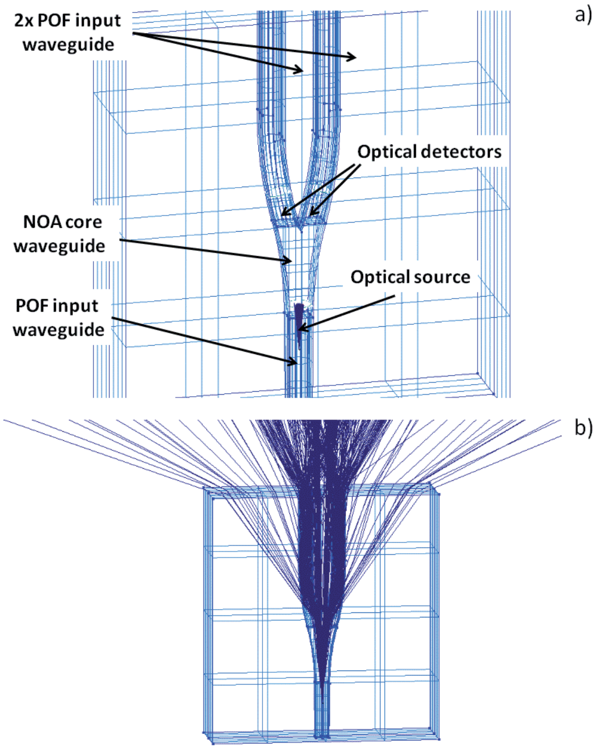

Fig. 4. a) Schematic view of the model of the designed splitters, b) view of the ray tracing diagram for 1x2 splitter.

Fig. 5 shows view on the input (Fig. 5a) and output signals (Fig. 5b - output signal for the left waveguide, Fig. 5c - signal for the right waveguide) of the designed splitter (structure PMMA/NOA) for operating wavelength 650 nm obtained by modeling Opticad software.

substrate	waveguide	output power (μW)		coupling ratio	losses (dB)
PMMA	NOA73	P1	8.59	52:48	2.22
		P2	8.00		
PMMI	NOA88	P1	8.68	51:49	2.16
		P2	8.36		

Tab. 4. Calculated output power for the coupler designed using Opticad software.

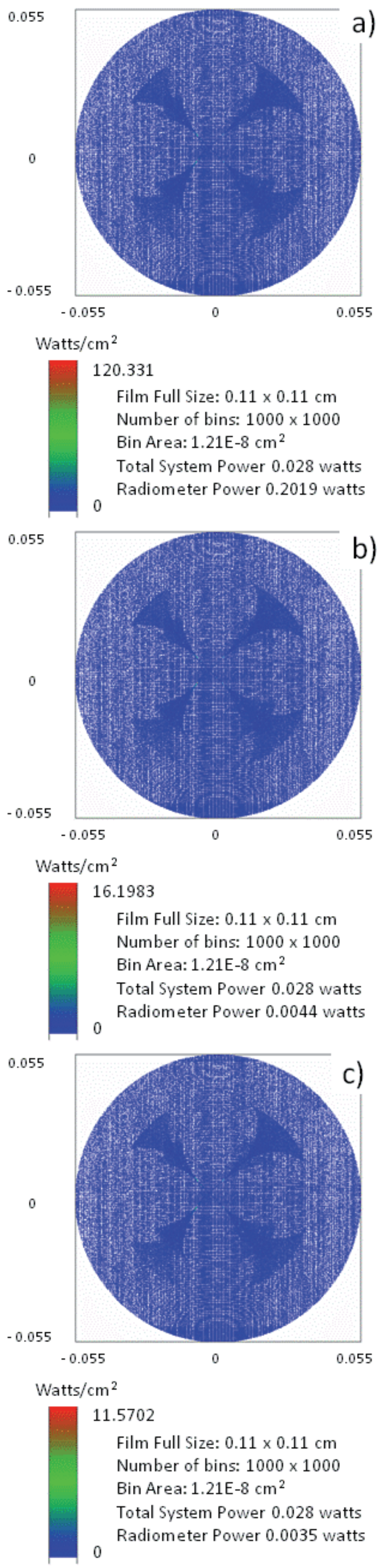

Fig. 5. Detector image for the structure of PMMA/NOA73 for the wavelength of 650 nm, a) input signal, b) output signal for the left waveguide, c) output signal for the right waveguide.

In Tab. 4, the results found for wavelength 650 nm and input power 28 μW, the same power that was used also for the measurement, are summarized.

3. Fabrication of the 1 x 2 Y Splitter

The fabrication process of the designed optical splitters is shown in Fig. 6 step by step.

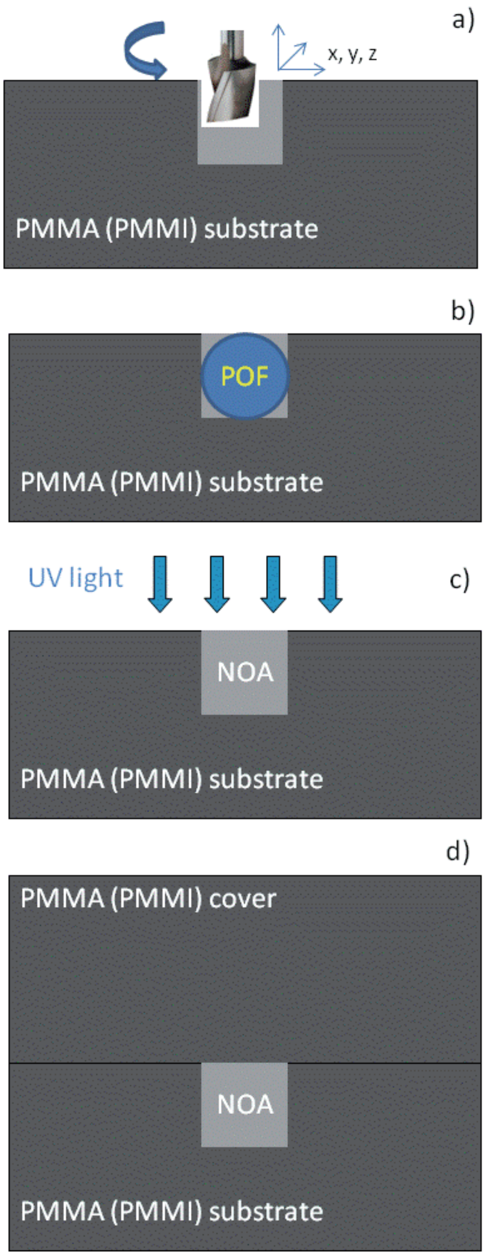

Fig. 6. Fabrication process of the optical splitters, a) CNC machining into polymer substrate, b) inserting of standard POF waveguide, c) filling up taper region with core layer and applying UV curing process, d) assembling top cover layer.

The Y-groove for waveguide layer into PMMA or PMMI substrate was fabricated by using CNC NONCO Kx3 milling machine (milling tool size of 0.8 mm, spindle 1800 rpm/min and moving 36 mm/min (Fig. 6a). Then we inserted standard POF waveguides (PFU-UD1001-22V) as the input/output waveguides into the groove (Fig. 6b). Next we filled up the taper region with NOA73 or NOA88 polymer and applied UV curing process (Fig. 6c). Finally top cover PMMA or PMMI was placed onto the structures (Fig. 6d).

4. Results

Prior fabrications of the 1x2 splitter we deposited core waveguide polymer NOA73 and NOA88 by using spin coating onto quartz glass and then we applied UV curing. These samples have thicknesses of several microns and they were used to measure transmission spectra. We also measured transmission spectra of the PMMA and PMMI substrates and cover layers. The measurement proved that these polymer materials had suitable properties for fabrication of our designed splitters (see Fig. 7).

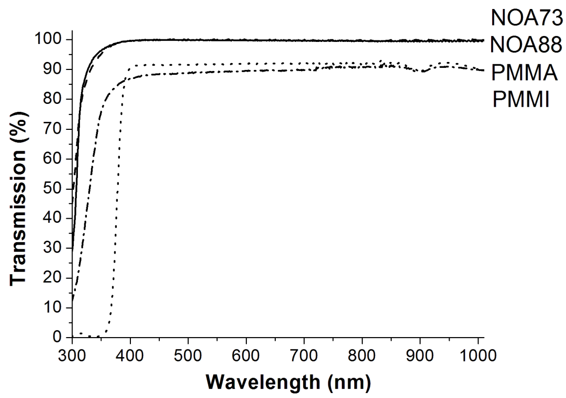

Fig. 7. Transmission spectra of waveguide core NOA73, NOA88 polymer and PMMA, PMMI substrates and cover layers.

The image of the fabricated structure is shown in Fig. 8. and Fig. 9. Fig. 8 shows a structure with Y-groove (picture without deposition core, waveguide layer and input/output POF waveguides) while Fig. 9 shows final structure with assembled POF input and output waveguides and NOA core waveguide layer. Parameters of the splitter were checked using optical microscope and the measurement revealed that it had good optical quality and dimension of the fabricated structure corresponded to the size of the proposed splitters. Fig. 10 shows splitter transmitting the optical signal at wavelength of 650 nm.

Fig. 8. Image of the 1x2 Y-groove substrate.

Insertion optical loss measurements were done at 532.8 nm (optical source Nd:YVO_4 laser), 650 nm (laser

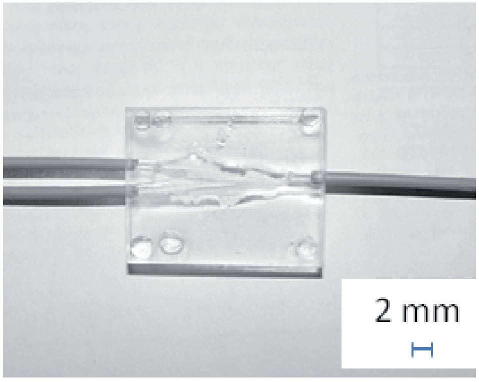

Fig. 9. Image of the 1x2 splitter fabricated from PMMA/NOA73 polymers with POF input/output waveguide.

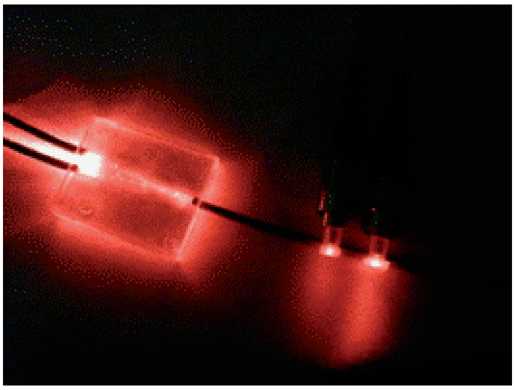

Fig. 10. Image of the 1x2 splitter transmitting the optical signal (650 nm).

Safibra OFLS-5 FP-650) and 850 nm (laser Safibra OFLS-5 DFB-850). The output light from the structures was measured by optical powermeter Anritzu ML910B with MA9802A probes. The schema of the measurement method is given in Fig. 11. The measurement starts with determining the optical power (P_{in}) coming from the source and passing though the reference POF fiber (Fig. 11.a) and then the power was measured separately for the left (P_{out1}) and right (P_{out2}) output branches of the splitter.

The insertion optical losses were calculated from equation (6) and the obtained data are summarized in Tab. 5.

$$L = -10 \cdot \log \frac{P_{out1} + P_{out2}}{P_{in}}. \tag{6}$$

The measurement of optical insertion losses proved that the sample deposited on the PMMA substrate with NOA73 core waveguide had optical losses 3.5 dB at 532 nm, 7.6 dB at 650 nm and 8.3 dB at 850 nm while the sample deposited on PMMI substrate with NOA88 core waveguide had optical losses 4.5 dB at 532 nm, 13.2 dB at 650 nm and 13.4 dB at 850 nm.

The splitters were tested by signal transmission being connected to the internet network and using two optoelectronic switches KCD-303P-A2 (KTI Networks). The schema of the measurement setup is shown in Fig. 12. We achieved the maximum possible transmission data rate, which provided computer network 60 Mb/s.

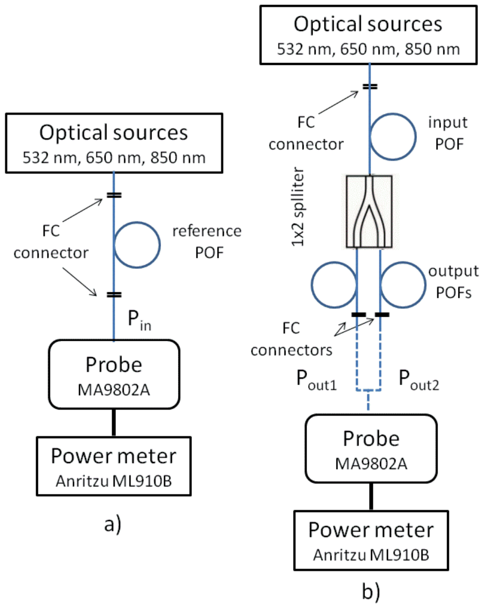

Fig. 11. Set up for insertion optical loss measurement.

substrate	waveguide	coupling ratio	losses (dB)		
			532 nm	650 nm	850 nm
PMMA	NOA73	49:51	3.5	7.6	8.3
PMMI	NOA88	52:48	4.5	13.2	13.4

Tab. 5. Insertion optical losses of the splitters.

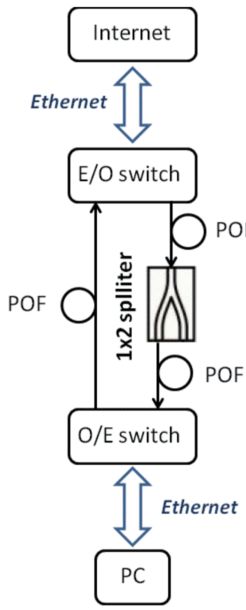

Fig. 12. Set up for testing transmission of the optical signal.

5. Conclusion

We have designed, realized and measured properties of the multimode polymer splitters. The design was done by ray tracing method using Opticad software. The materials of the actual splitter were Norland Optical Adhesives glues (NOA73 and NOA88) as optical waveguide layers on PMMA or PMMI substrates and cover layer. The designed structures were then realized by CNC engraving and the waveguiding pattern was hardened by the UV radiation.

The measurement of optical insertion losses proved that the best samples had optical losses 3.5 dB at 532 nm. Simulated values of optical losses were found to be around 2.2 dB, but in that values the intrinsic losses coming from the material of the waveguide are not included. The measured coupling ration 52:48 was very similar to the simulated one.

Acknowledgements

Our research is supported by the Ministry of Industry and Trade of the Czech Republic under project FR-TI3/797 and by grant CTU no. SGS11/156/OHK3/3T/13. Special thanks should be given to Lukáš Střižík and Tomáš Vítek for technical support.

References

[1] ZIEMANN, O., KRAUSER, J., ZAMZOW, P. E., DAUM, W. *POF Handbook: Optical Short Range Transmission Systems*. 2nd ed. Springer, 2008.

[2] LI, Y. P., HENRY, C. H. Silica-based optical integrated circuits. *IEE Proceedings-Optoelectronics*, 1996, vol. 143, no. 5, p. 263 to 280.

[3] SAKAI, A., FUKAZAWA, T., BABA, T. Low loss ultra-small branches in a silicon photonic wire waveguide. *IEICE Transactions on Electronics E Series C*, 2002, vol. 85, no. 4, p. 1033 to 1038.

[4] SUM, T. C., BETTIOL, A. A., KAN, J. A., WATT, F., PUN, E. Y. B., TUNG, K. K. Proton beam writing of low-loss polymer optical waveguides. *Applied Physics Letters*, 2003, vol. 83, no. 9, p.1707 to 1709.

[5] YABU, T., GESHIRO, M., OHASHI, M. Low-loss wide-angle y-branch optical waveguides. *Electronics and Communications in Japan (Part II: Electronics)*, 2005, vol. 88, no. 2, p. 11–18.

[6] GAO, Y., GONG, Z., BAI, R., HAO, Y.L., LI, X.H., JIANG, X.Q., WANG, M.H., PAN, J.X., YANG, J.Y. Multimode-waveguide-based optical power splitters in glass. *Chinese Physics Letters*, 2008, vol. 25, no. 8, p. 2912-2914.

[7] MIZUNO, H., SUGIHARA, O., JORDAN, S., OKAMOTO, N., OHAMA, M., KAINO, T. Replicated polymeric optical waveguide devices with large core connectable to plastic optical fiber using thermo-plastic and thermo-curable resins. *Journal of Lightwave Technology*, 2006, vol. 24, no. 2, p. 919-926.

[8] TAKAZEWA, Y., AKASAKA, S., OHARA, S., ISHIBASHI, T., ASANO, H., TAKETANI, N. Low excess losses in a Y-branching plastic optical waveguide formed through injection holding. *Applied Optics,* 1994, vol. 33, no. 12, p. 2307-2312.

[9] KLOTZBUECHER, T., BRAUNE, T., DADIC, D., SPRZAGALA, M., KOCH, A. Fabrication of optical 1x2 POF splitters using the Laser-LIGA technique. In *Proceedings Laser Micromachining for Optoelectronic Device Fabrication*, 2003, vol. 4941, p. 121-132.

[10] MIZUNO, H., SUGIHARA, O., KAINO, T., OKAMOTO, N., OHAMA, M. Compact Y-branch-type polymeric optical waveguide devices with large-core connectable to plastic optical fibers. *Japanese Journal of Applied Physics*, 2005, vol. 44, p. 8504-8506.

[11] EHSAN, A. A., SHAARI, S., RAHMAN, M. K. A. Low cost 1 × 2 acrylic-based plastic optical fiber coupler with hollow taper waveguide. *Piers Online*, 2009, vol. 5, no. 2, p. 129-132.

[12] EHSAN, A. A., SHAARI, S., RAHMAN, M. K .A. 1 x 2 Y-branch plastic optical fiber waveguide coupler for optical access card system. *Progress in Electromagnetics Research Pier*, 2009, vol. 91, p. 85-100.

[13] EHSAN, A. A., SHAARI, S., RAHMAN, M. K. A. Acrylic and metal based Y-branch plastic optical fiber splitter with optical NOA63 polymer waveguide taper region. *Optical Review*, 2011, vol. 18, no. 1, p. 80-85.

[14] PARK, H. J., LIM, K. S., KANG, H. S. Low-cost 1×2 plastic optical beam splitter using a V-type angle polymer waveguide for the automotive network. *Optical Engineering*, 2011, vol. 50, no. 7, p. 075002-075004.

[15] BELTRAMI, D. R., LOVE, J. D., LADOUCEUR, F. Multimode planar devices. *Optical and Quantum Electronics*, 1999, vol. 31, p. 307–326.

About Authors

Václav PRAJZLER was born in 1976 in Prague, Czech Republic. In 2001 he graduated from the Faculty of Electrical Engineering, Czech Technical University in Prague. Since 2005 he has been working at the Czech Technical University in Prague, Faculty of Electrical Engineering, Dept. of Microelectronics as a research fellow. In 2007 he obtained the PhD degree from the same university. His current research is focused on fabrication and investigation properties of the optical materials for integrated optics.

Ngoc Kien PHAM was born in 1985 in Thanh Hoa, Vietnam. In 2012 he graduated from the Faculty of Electrical Engineering, Czech Technical University in Prague. His master program was reached at the Dept. of Telecommunication Engineering, Faculty of Electrical Engineering, Czech Technical University in Prague and his master thesis was focused on the multimode polymer planar optic splitter.

Jarmila ŠPIRKOVÁ graduated from the Faculty of Natural Science, Charles University in Prague and from the Institute of Chemical Technology, Prague (ICTP). Now she is with the Dept. of Inorganic Chemistry at the ICTP. She has worked there continuously in material chemistry research and since 1986 she has been engaged in planar optical waveguides technology and characterization. She is an Assistant Professor at the ICTP giving lectures on general and inorganic chemistry.