Planar Large Core Polymer Optical 1x2 and 1x4 Splitters Connectable to Plastic Optical Fiber

Václav PRAJZLER [1], Miloš NERUDA [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 new approach to design and fabricate multimode 1 x 2 and 1 x 4 Y optical planar power splitter suitable for low-cost short distance optical network. The splitters were designed by beam propagation method using BeamPROP™ software. The dimensions of the splitters were optimized for connecting standard plastic optical fibre with 1 mm diameter. New Norland Optical Adhesives 1625 glues were used as optical waveguide layers and the design structures were completed by CNC engraving on poly(methyl methacrylate) substrate. The best parameters that were achieved with 1x2 splitter were insertion loss around 4.1 dB at 650 nm and the coupling ratio 52:48; the best one of the 1x4 splitters had at 650 nm insertion loss around 17.6 dB.*

Keywords

Multimode 1x4 coupler, optical planar waveguide, polymer, beam propagation method.

1. Introduction

Single or multimode mode silica optical fibers are currently used for long haul backbone optical communication systems. Most common type of single-mode fibers have core diameter of 8–10 µm and cladding layer is 125 µm. Common multi-mode fibers for communication systems have core diameter 50 µm or 62.5 µm with 125 µm cladding layer. Nowadays, in short distance communication networks, plastic optical fibers (POF) are becoming to be applied [1] and such networks are used mainly for automotive, private office, home and sensor communications systems. POF standardly have core layer diameter 980 µm and diameter of the cladding layers is 1000 µm.

The developed new photonics structures including optical splitters, switches, demultiplexers, filters, routers are becoming very important for future photonics POF systems. Among them the most important photonics structures are Y-splitters. These devices are key components in photonics applications for signal processing and signal routing. The Y-splitter waveguides are used for distributing signals from one port to two (or more) output ports.

Up to now the structures for distribution and signal processing for photonics applications for standard backbone optical communication systems have been mainly fabricated from semiconductors, glass and optical crystals. Such materials have suitable properties but needed deposition technologies that are complex, expensive and also environment threatening and this is why new technology processes with using new materials are being intensively researched. Very promising alternative for photonics applications can be polymers. Polymer materials have been intensively studied for photonics applications in the last decade especially because of their high transparency from visible to infra red wavelengths, well-controlled refractive indices, reasonable temporal and temperature stability, low optical losses, easy fabrication process and, last but not least, also low cost [2-7]. Moreover, many polymers are also environment-friendly materials and this, together with their versatility, makes them an appealing alternative for silicon, glasses and optical crystals.

In recent years, construction of the splitters and optical couplers has been reported by many research groups in various papers [8-14] but the core sizes of the reported Y-dividers were mostly smaller than 100 µm [15], [16]. Only a very limited number of the research teams have published papers describing a planar optical splitter for multimode fiber with large core diameters around 1000 µm [17-22].

We have already reported [23] about properties of the multimode polymer 1x2 splitters designed by ray tracing method. Optical core waveguide materials of the reported splitter were Norland Optical Adhesives (NOA 73 and NOA 88) and we used two types of the substrates and cover layers made of poly(methyl methacrylate) or poly(methylmethacry-limide).

In this paper we are going to report about 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 poly(methyl-methacrylate) substrate used as substrates and cover layers. The advantage of this new NOA1625 core waveguide layer is higher value (comparing with commonly used polymer-based waveguide layers) of the refractive index, which makes it possible to design the splitter with more compact dimensions. Our proposal is constructed for input/output standard 1 mm POF waveguides. Modeling and optimization of the splitters were done by using beam propagation method, which allows for more accurate design of the splitter.

2. Design of the Multimode Splitters

2.1 Beam Propagation Method

The splitters were proposed by using finite difference beam propagation method (BPM). BPM is the most widely used propagation technique for modeling integrated photonic structure and most commercial software for such modeling is based on it. BPM method solved the parabolic or paraxial approximation of the Helmholtz equation. In our case we used “transparent"” boundary conditions following [24], [25]. BPM is essentially a particular approach for approximating the exact wave equation for monochromatic waves, and makes easier to solve the resulting equations numerically. For the design we used 2D BeamPROP^{TM} software supported by RSoft design group [26].

2.2 Design of the 1x2 Splitter

We used a new type of the UV photopolymer supported by Norland Optical Adhesives glues as optical core waveguide layers (NOA1625) and Poly(methyl-methacrylate) (PMMA) supplied by Evonik Industries AG was used as the substrates and cover protection layers. The cross section of the designed optical planar waveguide is shown in Fig. 1.

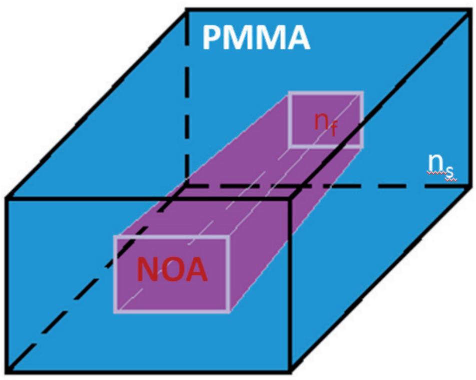

Fig. 1. Schematic view of the cross-section for the proposed multimode optical planar waveguide ($n_c = n_s$).

The main advantage of the NOA1625 core waveguide layer is higher value of the refractive index comparing with that used with other core waveguide materials (NOA72, NOA73, NOA88, Photobond 300, Epotek OG113, Su-8, and etc.). Production of photonic structures with waveguide core layer made from material with higher index of refraction allows realizing new photonic structures with compact dimensions and better optical properties. Polymer materials were deposited by spin coating on silica on silicon substrate and refractive indices of deposited materials were then measured by dark mode spectroscopy using prism-coupler system Metricon 2010 (see Fig. 2).

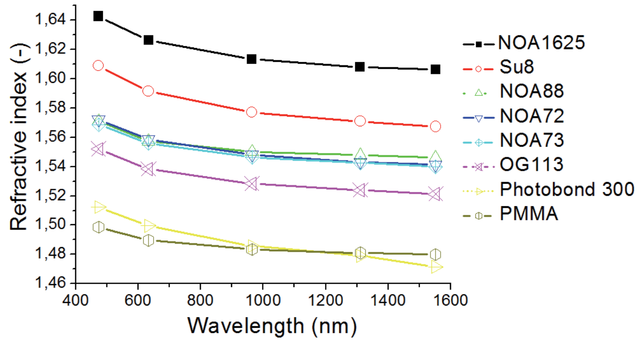

Fig. 2. Refractive indices of waveguide core materials including NOA1625 used for designed splitter and PMMA substrate.

Before the modeling and optimization geometrical dimensions of the design Y splitter by using BPM method we calculated geometrical dimensions of the splitters by analysis for a lossless Y-junction published by Beltrami [27] and applied for the design splitters with large waveguide core by Ehsan [28]. The geometrical structure of the designed optical planar multimode splitter is shown in Fig. 3.

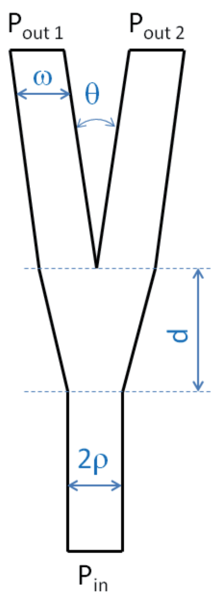

Fig. 3. Geometrical structure of the proposed 1 x 2 Y optical power splitter.

Beltrami showed [27] that for a lossless Y-splitter the branching angle Ω was specified as:

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

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 refractive index of the core waveguide material and n_s is refractive index of the cladding material. D is the normalized value and it is defined by 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 ($\omega = 2\rho$) [23]. We also calculated the value of numerical aperture NA. NA is a dimensionless number that characterizes the range of angles over which the optical waveguide structures can accept light:

$$NA = \sqrt{n_f^2 - n_s^2}\ . \tag{4}$$

Calculation of geometrical dimensions of the designed PMMA/NOA1625 splitters for wavelength 532 nm, 650 nm and 850 nm are summarized in Tab. 1.

PMMA/NOA1625						
λ (nm)	n_f (-)	n_s (-)	θ (°)	Ω (°)	d (mm)	NA (-)
473	1.643	1.499	24.152	12.09	2.44	0.67
532	1.636	1.495	23.96	11.98	2.46	0.66
650	1.625	1.489	23.61	11.82	2.50	0.65
850	1.618	1.485	23.39	11.70	2.52	0.64

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

After calculating the dimensions of the designed optical splitters by Beltrami analysis the dimensions of the splitters were more precisely specified by using BPM by BeamPROP^{TM} software. The results of the simulations for the optimized structure that had the best parameters are shown in Fig. 4 and Fig. 5.

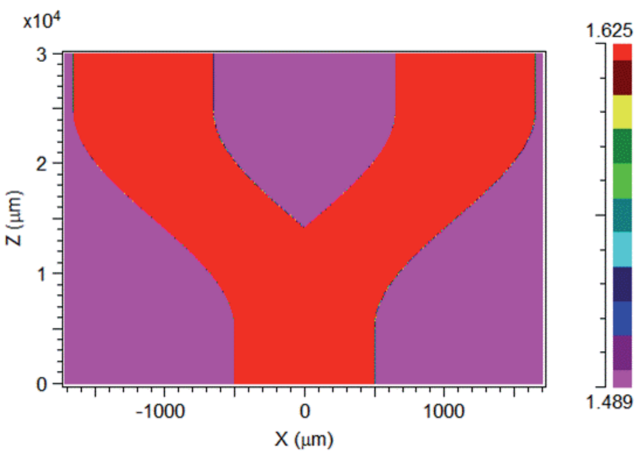

Fig. 4. Computed index profile for the best optimized structure.

Fig. 4 shows the computed refractive index profile of the optimized structure with the pertinent dimensions while in Fig. 5 the propagation of the signal is given. The graph shows that the power division is perfectly symmetrical. Modeling was done for a wavelength 650 nm and for refractive indices of 1.625 (waveguide NOA layer) and 1.489, respectively (PMMA substrate).

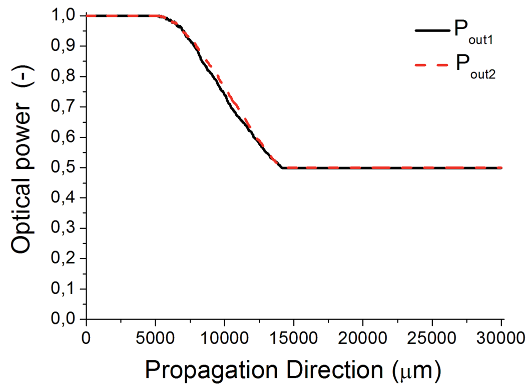

Fig. 5. Results of simulation of the optimized 1x2 Y POF splitter for 650 nm (Normalized optical signal).

2.3 Design of the 1x4 Splitter

After designing the 1x2 splitter we started to design the structure of the 1x4 divider. The geometrical structure of the designed optical planar multimode 1x4 splitter is shown in Fig. 6.

The structure of the 1x4 splitter consists of one splitter 1x2 followed by next two 1x2 splitters. This cascade arrangement allows for splitting one input optical single to four output optical signals. The results of the simulation of the optimized 1x4 structure having the best parameters are shown in Fig. 7. In it, Fig. 7a shows computed refractive index profile and in Fig. 7b there is shown how the propagation signals is almost symmetrically divided (approximately P_{out1} = 24.4%, P_{out2} = 24.2%, P_{out3} = 25.5%, P_{out1} = 25.9%).

3. Fabrication of the Splitters

The fabrication process of the designed optical splitters is shown in Fig. 8 step by step and was already described in our previous paper [23]. 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. 8a)). Then we inserted standard POF waveguides (PFU-UD1001-22V) as the input/output waveguides into the groove (see Fig. 8b). Next we filled up the taper region with NOA1625 polymer and applied UV curing process (see Fig. 8c). Finally top cover PMMA is placed onto the structures (see Fig. 8d).

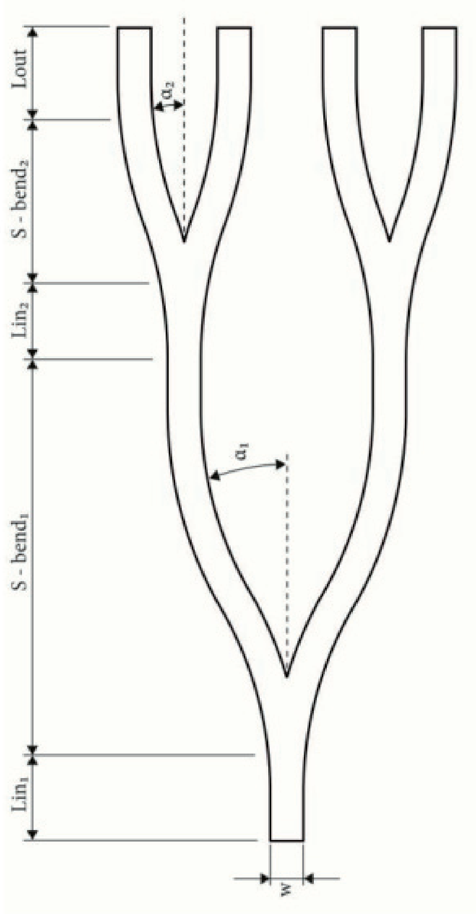

Fig. 6. Schematic view of the proposed 1x4 Y splitter.

4. 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. The images of the fabricated Y-groove structures after the step illustrated in Fig. 8a are shown in Fig. 9 (core waveguide layer, input/output POF waveguides and cover protection layer are not yet done there). Fig. 9a shows a substrate with the Y-groove for 1x2 splitter and Fig. 9b shows a substrate with the Y-groove for 1x4 splitter.

Fig. 10 shows the final structure (with assembled POF input and output waveguides and NOA core waveguide layer and cover PMMA layer) transmitting the signal from a FLS-240 laser at 635 nm. Fig. 10a shows the 1x2 splitter and Fig. 10b shows the 1x4 splitter.

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 outputs light from the structures were measured by optical powermeter Anritsu ML910B with MA9802A probes. We used the same arrangement as described in [23]. The obtained results are summarized in Tab. 2.

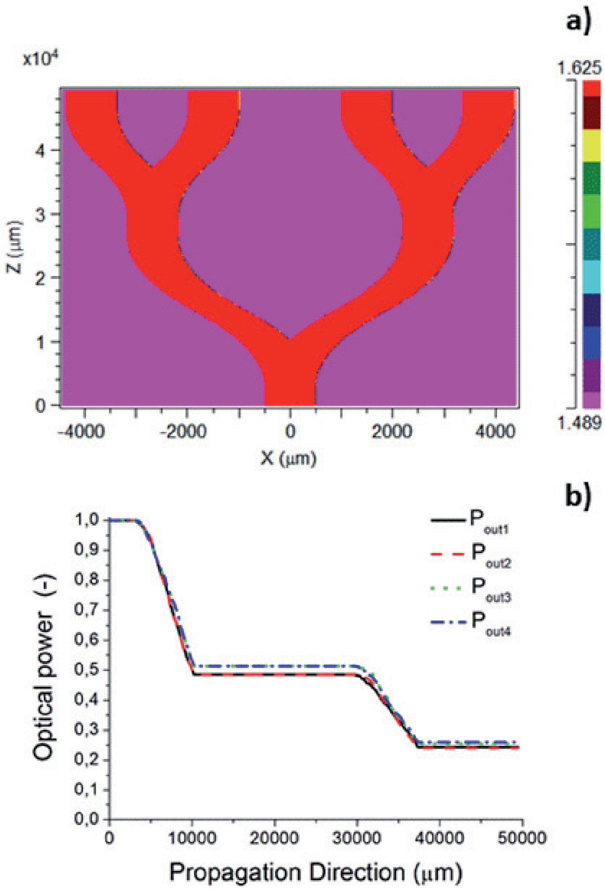

Fig. 7. Results of simulation for the optimized 1x4 Y POF splitter, a) The computed index profile for optimized structure of 1x4 splitter, b) Normalized optical signal propagating at 650 nm.

splitter	coupling ratio	losses (dB)		
		532 nm	650 nm	850 nm
1x2	52:48	2.7	4.1	4.5
1x4	26:27:23:44	14.7	17.6	13.9

Tab. 2. Insertion optical losses of the splitters.

The 1x2 splitters were tested by signal transmission being connected to the internet network and using two optoelectronic switches KCD-303P-A2 (KTI Networks) and we achieved the maximum possible transmission data rate, which provided computer network 100 Mb/s.

5. Conclusions

We designed, realized and measured properties of multimode polymer 1x2 and 1x4 splitters. The design was done by beam propagation method using RSoft software. For the splitters we used new NOA 1625 core waveguide layers and PMMA materials were used for substrate and cover protection layer. The designed structures were then realized by CNC engraving and the waveguiding pattern was hardened by the UV radiation.

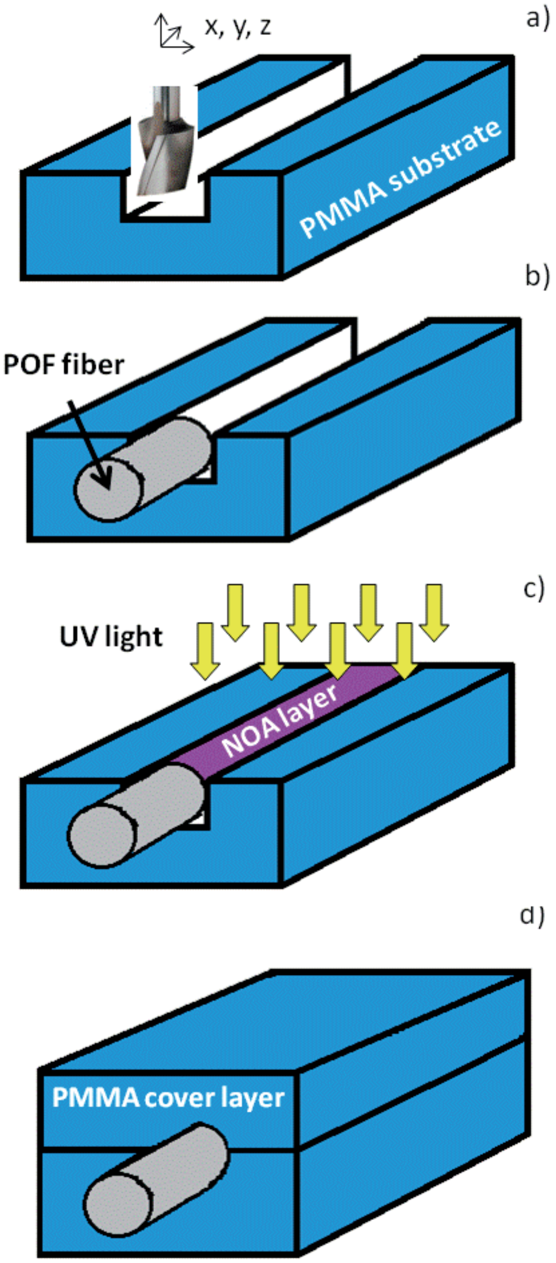

Fig. 8. Fabrication process for the optical splitters, a) CNC machining into polymer substrate, b) inserting of standard POF waveguide, c) filling up taper region with core layer and applying UV curing process, d) assembling top cover layer.

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 measured coupling ratio was 52:48. The 1x4 splitter had optical losses 14.7 dB at 532 nm, 17.6 dB at 650 nm and 13.9 dB at 850 nm.

The splitters may find their application in the low cost short distances optical networks.

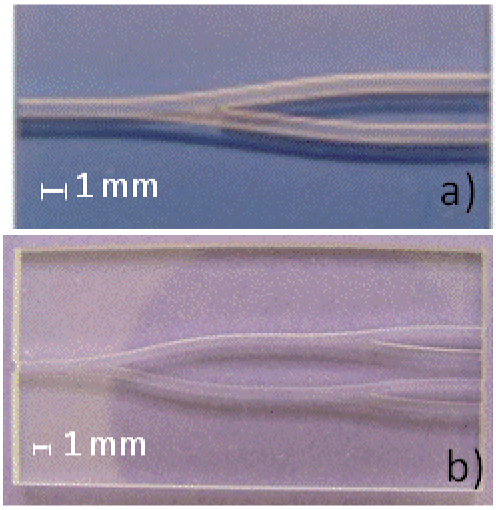

Fig. 9. Image of the Y-groove substrate for the splitters a) 1x2, b) 1x4.

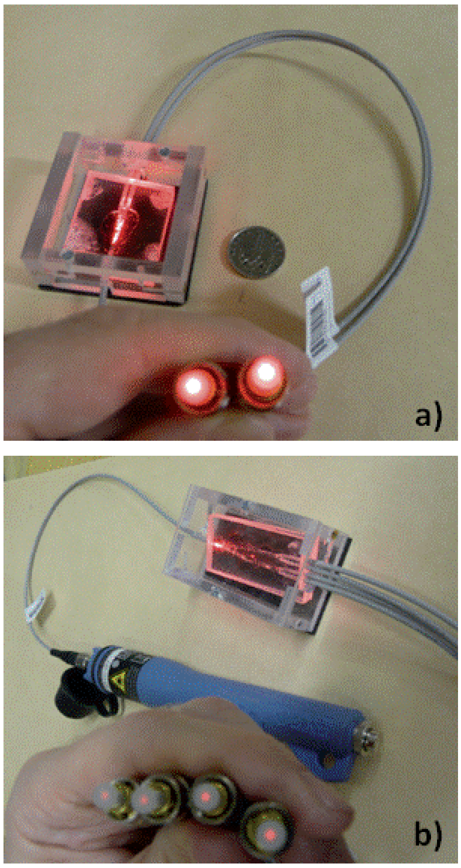

Fig. 10. Images of splitters transmitting optical signal (λ = 635 nm) a) splitter 1x2 Y, b) splitter 1x4 Y.

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 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] WONG, W.H., LIU, K.K. CHAN, K.S., PUN, E.Y.B. Polymer devices for photonics applications. *Journal of Crystal Growth,* 2006, vol. 288, no. 1, p. 100-104.

[3] MA, H., JEN, A.K.Y., DALTON, L.R. Polymer-based optical waveguides: Materials, processing, and devices. *Advanced Materials*, 2002, vol. 14, no. 19, p. 1339-1365.

[4] ELDADA, L. Optical communication components. *Review of Scientific Instruments*, 2004, vol. 75, no. 3, p. 575-593.

[5] CHRISTIANSEN, B. M., SCHOLER, M., KRISTENSEN, A. Integration of active and passive polymer optics. *Optics Express*, 2007, vol. 15, no. 7, p. 3931-3939.

[6] BECHE, B. Integrated photonics devices on Su8 organic materials. *International Journal of Physical Sciences*, 2010, vol. 5, p. 612 to 618.

[7] PRAJZLER, V., KLAPUCH, J., LYUTAKOV, O., HÜTTEL, I., ŠPIRKOVÁ, J., NEKVINDOVÁ, P., JEŘÁBEK, V. Design, fabrication and properties of rib poly (methylmethacrylimide) optical waveguides. *Radioengineering*, 2011, vol. 20, p. 479-485.

[8] KECK, D. B., MORROW, A. J., NOLAN, D. A. Passive components in the subscriber look. *Journal of Lightwave Technology*, 1989, vol. 7, no. 11, p. 1623-1633.

[9] ZHANG, G., HONKANEN, S., NAJAFI, S. I., TERVONEN, A. Integrated 1.3 μm /1.5 μm wavelength multiplexer and 1/8 splitter by ion-exchange in glass. *Electronics Letters*, 1993 vol. 29, no. 12, p. 1064-1066.

[10] 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, p. 1033–1038.

[11] 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, p. 1707-1709.

[12] 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.

[13] WANG, S., VAIDYANATHAN, V., BORDEN, B. Polymer optical channel waveguide components fabricated by using a laser-direct writing system. *Journal of Applied Science & Engineering Technology*, 2009, vol. 3, p. 47-52.

[14] ELDADA, L., SHACKLETTE, L. W. Advances in polymer integrated optics. *IEEE Journal of Selected Topics in Quantum Electronics*, 2000, vol. 6, no. 1, p. 54-68.

[15] KAGAMI, M., ITO, H. Multimode power divider using radiation from tight bending waveguide. *Journal of Lightwave Technology*, 1998, vol. 16, no. 11, p. 2028-2033.

[16] 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.

[17] 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.

[18] 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.

[19] 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.

[20] EHSAN, A. A., SHAARI, S., RAHMAN, M. K. A. Design and fabrication of an acrylic-based 1x2 POF coupler using CNC machining. In *Proc. of IEEE International Conference on Semiconductor Electronics*. Johor Bahru (Malaysia). 2008, p. 340-344.

[21] 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.

[22] KWANG, T. K., MIN, K. K. Low-loss 1 x 2 plastic optical fiber coupler incorporating a tapered polymeric waveguide and plastic optical fiber transition regions. *Japanese Journal of Applied Physics*, 2012, vol. 51, no. 9, p. 8504-8506.

[23] PRAJZLER, V., PHAM, N. K., ŠPIRKOVÁ, J. Design, fabrication and properties of the multimode polymer planar 1 x 2 Y optical splitter. *Radioengineering*, 2012, vol. 21, no. 4, p. 1202-1207.

[24] HADLEY, G. R. Transparent boundary condition for the beam propagation method. *Journal of Quantum Electron*, 1992, vol. 28, no. 1, p. 363–370.

[25] USER GUIDE manual, RSoft Design Group, Inc.: BeamPROP 8.3

[26] BeamPROP™ software supported by RSoft design group. [Online] Available at: http://www.rsoftdesign.com

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

[28] 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.

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, Department of Microelectronics. Since 2005 he has been working at the Czech Technical University in Prague, Faculty of Electrical Engineering, Department of Microelectronics as a research fellow. In 2007 he obtained the PhD degree from the same university. His current research is focused on design, fabrication and investigation of properties of new optical materials for photonics applications.

Miloš NERUDA was born in 1975. His bachelor degree was reached at the Dept. of Microelectronics at CTU in Prague in 2012 and his bachelor thesis was focused on the design, fabrication and investigated properties of multimode polymer planar optical power splitters. His current research is focused to design photonics structures.

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, ICTP. She has worked there continuously in materials chemistry research and since 1986 she has been engaged in planar optical waveguides technology and characterization. She is the Assistant Professor at the ICTP giving lectures on general and inorganic chemistry.