Flexible Polymer Planar Optical Waveguides

Václav PRAJZLER [1], *Pavla NEKVINDOVÁ* [2], *Petr HYPŠ* [1], *Oleksiy LYUTAKOV* [2], *Vítězslav JEŘÁBEK* [1]

[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

Abstract. *We report about design, fabrication and properties of flexible polymer optical planar waveguides made of epoxy novolak resin as planar waveguides deposited on various foil substrates. The design of the presented planar waveguides was realized on the bases of modified dispersion equation and was schemed for 633 nm, 850 nm, 1310 nm and 1550 nm wavelength. Propagation optical loss measurements were done by the fibre probe technique at wavelegnth 633 nm (He-Ne laser) and samples have optical losses lower than 2 dB·cm^{-1}. Unlike the up-to-now presented structures our constructin is fully flexible what makes it possible to be used in innovative photonics structures.*

Keywords

Optical planar flexible waveguide, polymer, epoxy novolak resin.

1. Introduction

In recent years, there has been a continuing growth of the demand for data communications link capacity. Existing interconnection technologies for shorter distance used mainly metal copper wiring connection, but due to the rising data-rates and their sensitivity to electromagnetic interference, they soon will be unable to keep up [1], [2]. Therefore it seems that light as a transmission medium for the future interconnections (rack-to-rack, board-to-board, multi-chip modules, on-board) is a right choice. Optical interconnects have many advantages over wire tracks: higher bandwidth, immunity from crosstalk and electromagnetic interference, light weight, low skew, jitter, etc. [3], [4].

Conventional optical link consists of glass optical fiber and traditional photonics planar structures and devices have been made of semiconductors, inorganic crystals and glasses. Though these materials are good candidates for common photonics structures they are not enough flexible and it is difficult to use them for new photonics devices which are continuously miniaturized and integrated [5].

Polymer materials for the fabrication of flexible planar optical waveguides appeared to be a good choice for their excellent optical properties such as 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 low costs, and, last but not least, their mechanical properties [6-13].

There are a number of different polymers that can be considered for use in new photonics structures and devices. Most of the early work was focused to the Polymethylmethacrylate as the waveguide material [14], [15]. Recently quite a lot of researches groups examined a new type of polymers for photonics applications and as many companies are very active in this field such polymers are nowadays commercially available. It concerns, e.g., Acrylate (AlliedSignal), Acrylate Polyguide™ (DuPont), Acrylate Benzocyclobutene (Dow Chemical), Chloro-fluorinated polyimides (Samsung), Deuterated polysiloxane (NTT), Epoxy novolak resin (Micro Resist Technology), Fluorinated polyimide and Ultradel 9000 series polyimide (Amoco Chemicals), Halogenated acrylate, Polyetherimide (General Electric), Polycarbonate with CLD-1 chromophore (PacificWave), Polycarbonate (JDS Uniphase), Polyurethane (Lumera), ZPU resin (ChemOptics Exguide™), etc. [16-19].

Integration of optical waveguides and opto-electronic components inside a flexible foil introduces a complete new concept of flexibility into the on-board optical communications [5]. For our research, we chose two types of epoxy novolak resin (ENR) Su8-5 and Su8-50 supported by Micro resist technology GmbH as a core waveguide material. This polymer was chosen for its excellent properties (optical losses 2 dB·cm^{-1} at 980 nm, 0.77 dB·cm^{-1} at 1310 nm, and 1.71 dB·cm^{-1} at 1500 nm) [20-22] and feasible fabrication process. For a substrate, we used Polymethylmethacrylate (PMMA) and commercially available CL400 and PET foil supported by Omniplast because of their suitable properties, mainly low value of the refractive indices.

2. Design of the Planar Waveguides

The optical planar waveguide is a fundamental element for realization of optical ridge or channel waveguides that can be used for interconnection of various devices of optical integrated circuits and photonics structures.

In our case planar optical waveguide is a step-index structure and consists of a high-index dielectric layer surrounded on upper and lower sides with lower index materials (Fig. 1). If the cover and substrate materials have the same refractive index, the waveguide is called symmetric; otherwise the waveguide is called asymmetric.

Here we are going to design optical planar waveguides with polymer foil substrate, Su8 polymer waveguides; the upper side will be left open so that the air will act as a "cover" (n_c).

Fig. 1. Schema of an optical planar waveguide.

The index of refraction of the guiding slab n_f must be higher than that of the substrate materials n_s, or cover materials n_c in order to ensure total internal reflection occurring at the interfaces [23].

$$n_f > n_s, n_f > n_c . \qquad (1)$$

Thickness h_f of the core of the optical waveguide film was calculated by using modification of dispersion equation (2), number of guided modes m is determined from equation (3) [24]:

$$h_f = \frac{\lambda_0}{2\pi\sqrt{n_f^2 - n_s^2}} \left\{ n\pi + \mathrm{arctg}\left[p\sqrt{\frac{n_s^2 - n_c^2}{n_f^2 - n_s^2}} \right] \right\}, \qquad (2)$$

$$m = INT\left\{ \frac{2}{\lambda_0} h_f \sqrt{n_f^2 - n_c^2} - \frac{1}{\pi}\mathrm{arctg}\left[p\sqrt{\frac{n_s^2 - n_c^2}{n_f^2 - n_s^2}} \right] \right\} \qquad (3)$$

where λ_0 is operating wavelength, n is an integer number $n = 0, 1, 2 \ldots$, and p is for the TE mode

$$p = 1 \qquad (4)$$

and for the TM mode

$$p = \left(\frac{n_f}{n_s} \right)^2 . \qquad (5)$$

Before the actual proposal the optical waveguide layer (Su8-50 and Su8-5) were deposited on a glass substrate and then refractive indices of Su8 polymers and substrate foils that are needed for the calculation were measured by prism coupling method (Fig. 2). The figure shows that the values of the refractive indices decreased with the increasing wavelengths and also that the foils used for the substrate had lower refractive indices than Su8 waveguide materials.

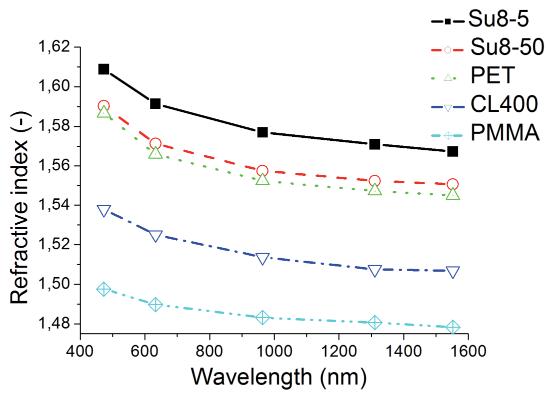

Fig. 2. Refractive indices of Su8 waveguide layer and PET, CL400, PMMA substrate.

Refractive indices for the substrate PMMA, CL400, PET and Su8-50, Su8-5 waveguides layers used for the design of the planar waveguides are listed in Tab. 1.

Wavelength (nm)	Refractive indices (-)				
	Substrates foil n_s			Waveguides layer n_f	
	PMMA	CL400	PET	Su8-50	Su8-5
633	1.4898	1.5251	1.5660	1.5713	1.5914
850	1.4855	1.5175	1.5573	1.5622	1.5816
1310	1.4807	1.5076	1.5474	1.5525	1.5709
1550	1.4783	1.5068	1.5453	1.5508	1.5673

Tab. 1. Refractive indices used for the design of the PMMA substrate, Su8-50 and Su8-5 waveguide layer.

The minimal calculated thickness for four wavelengths (633, 850, 1310, 1550 nm) of the designed single mode Su8-50 and Su8-5 planar optical waveguides are listed in Tab. 2. The results of mode calculations performed for 633 nm for TE for the first 20 modes concerning the waveguide structure described above are shown in Fig. 3.

Wavelength (nm)	mode	PMMA Su8-50	PMMA Su8-5	CL400 Su8-5	PET Su8-5
		h_f (μm)			
633	TE_0	0.21	0.20	0.33	0.48
	TE_1	0.86	0.76	1.17	1.59
850	TE_0	0.32	0.28	0.46	0.66
	TE_1	1.20	1.06	1.60	2.20
1310	TE_0	0.52	0.45	0.62	1.04
	TE_1	1.92	1.69	2.22	3.46
1550	TE_0	0.61	0.53	0.83	1.27
	TE_1	2.27	2.02	2.90	4.24

Tab. 2. Calculated minimum thicknesses for planar waveguides for PMMA. CL400. PET substrates and Su8-50. Su8-5 waveguide and air cover layer.

For example for PMMA/Su8-50 single mode waveguide structure we achieved the thickness of the waveguide layer h_f 0.21 μm for 633 nm and the thickness h_f 0.32 μm for 850 nm. For bigger thickness h_f than 0.52 μm for 1310 nm and 0.61 μm for 1550 nm waveguides became multimode (for more details see Tab. 2).

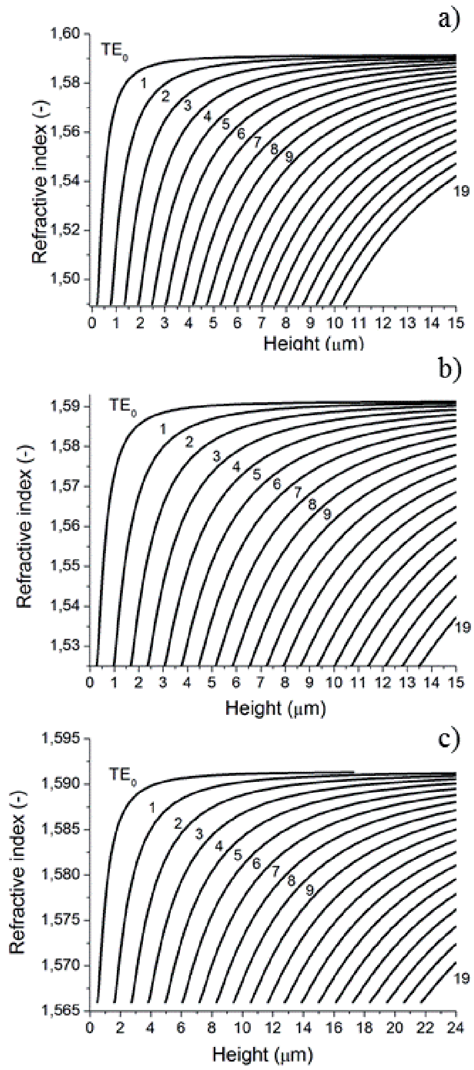

Fig. 3. TE mode calculation of the polymer planar waveguides for operation wavelength 633 nm for structures: a) PMMA/Su8-5, b) CL400/Su8-5 and c) PET/Su8-5.

3. Fabrication of the Waveguides

The experiments were performed on three types of substrates PMMA, CL400 and PET foils and two types of waveguide layers Su8-50 and Su8-5 (epoxy novolak resin). Fabrication process of the planar polymer flexible waveguides is illustrated in Fig. 4 step by step. PMMA foils for the substrates were made by dissolving pieces of PMMA in dichloroethane; this process needed some four to five days. The obtained solutions were let to dry for few days in petri dishes having different diameters. The dried substrates were removed from the petri dishes and cut for desired dimensions. Then polymer ENR waveguide layers were deposited on PMMA substrate by using spin coating (Fig. 4a); after that step soft bake process was applied at 50°C for 30 min in order to evaporate the remaining solvent (Fig. 4b). Then we applied UV curing process (Fig. 4c) and finally post exposure bake was done (Fig. 4d). Similar processes (except the step a) were applied for used CL400 and PET substrates.

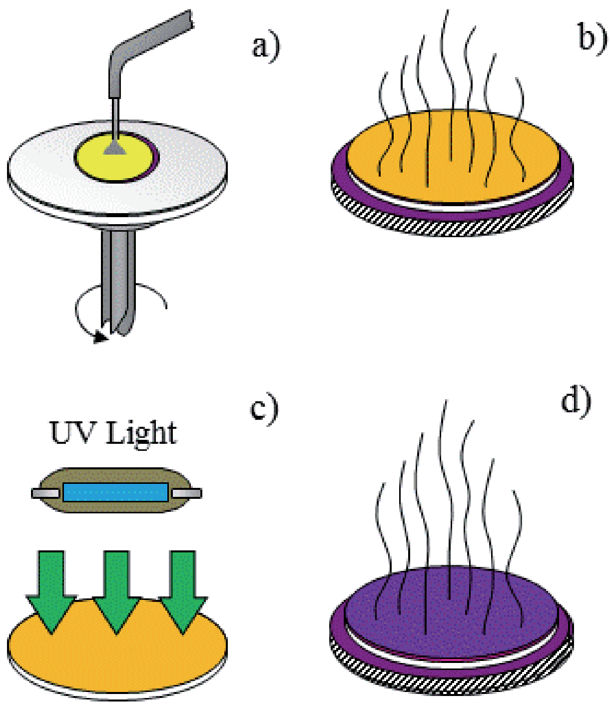

Fig. 4. Fabrication process for flexible planar optical waveguides: a) deposition of Su8 core waveguide layer, b) soft bake process, c) UV curing process, d) post exposure bake.

4. Results

The thicknesses of the fabricated PMMA flexible substrate were measured by dial thickness gauge LIMIT12.5/0.001 mm, while the thicknesses of the waveguides core layers were measured by profile-meters Talystep Hommel Tester 1000. The experimentally found thicknesses of the structure were as follows: flexible polymer PMMA substrates 30 μm to 500 μm depending on the amount of the polymer casted into the mould; CL400 foil 500 μm and PET substrate 1000 μm. The thicknesses of the polymer waveguide layers were from units to 60 μm, depending on the rate of spinning of the coater during the deposition.

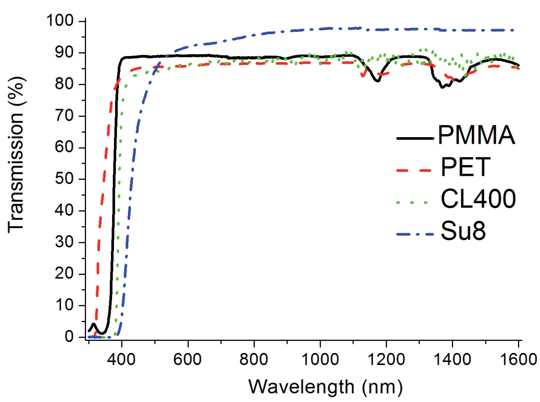

Fig. 5. Transmission spectra of PMMA, PET, CL400 substrates and Su8 waveguide layers.

Transmission spectra of the used substrates and Su8 waveguide layers were collected by UV-VIS-NIR Spectrometer (UV-3600 Shimadzu) in the spectral range from 300 to 1600 nm and are given in Fig. 5. Obviously the waveguide layer is transparent within the whole range of the measured wavelengths. Polymer substrates revealed two absorption peaks in the near infrared wavelength region, which can be attributed to the vibrational overtones of C–H bonds.

Waveguiding properties of the flexible ENR planar waveguides were examined by dark mode spectroscopy using Metricon 2010 prism-coupler system [25-27] (Fig. 6).

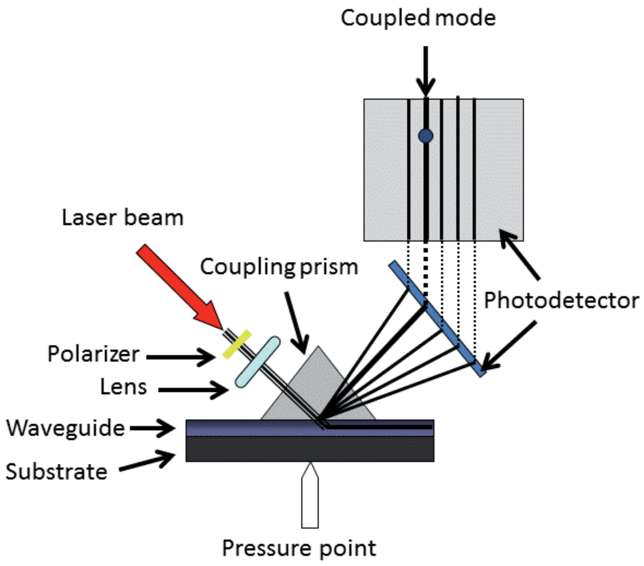

Fig. 6. Schematic view of the dark mode spectroscopy measurement.

The measured sample is brought into contact with the base of a couple prisms by means of a pneumatically-operated coupling head leaving narrow air gap between the waveguide film and the prism. Laser beam strikes the base of the prism and is totally reflected at the prism base onto a photodetector at certain discrete values of the incident angle Θ called mode angles. Photons can tunnel across the air gap into the waveguide film and enter into a guided optical propagation mode causing a sharp drop of the intensity of light reaching the detector [25].

The waveguiding properties were measured at five wavelengths (473, 633, 964, 1311 and 1552 nm). Fig. 7a gives an example of measured mode spectra of the multimode CL400/Su8-50 waveguide and the particular modes are signified by the arrows (26 modes in whole), designative for calculation of pertinent refractive index depth profile. All the refractive index depth profiles are then illustrated in Fig. 7b giving confirmation of a step-like character of all the profiles of 18 µm thick waveguiding layer. They also showed decrease of the refractive index values with the increasing wavelengths (see also Fig. 2).

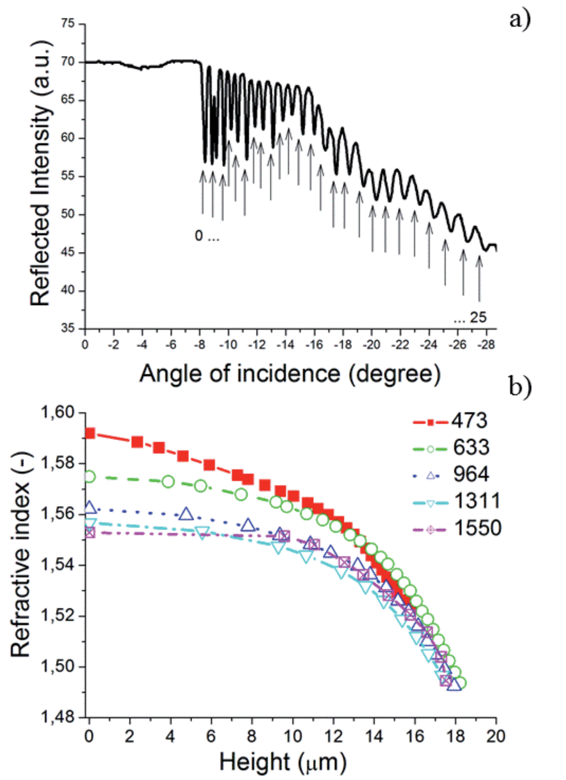

Fig. 7. Evaluation of the refractive indices depth profile of Su8-50 waveguide for various wavelengths for TE modes.

Mode pattern for Su8-50 optical planar waveguide deposited on PMMA foil substrate for three wavelengths (473, 633 and 1552 nm) is shown in Fig. 8. The arrows ① denote the first mode of the Su8 waveguide layer respective to the actual wavelengths, the arrows ② close to the edges of strong peaks show where the PMMA substrate begins. Incident angles ① for particular wavelengths are as follows: -7°15′ for 473 nm corresponds to refractive index of Su8 polymer 1.6116; -7°12′ for 633 nm corresponds to refractive index of Su8 polymer 1.5925 and finally angle -6°19′ for 1552 nm corresponds to refractive index of Su8 polymer 1.5702.

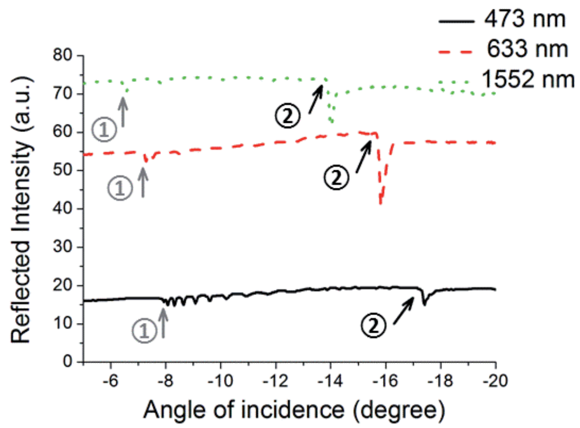

Fig. 8. Mode pattern of Su8-50/PMMA foil planar waveguides (TE modes). For easy orientation the curves for only three wavelengths are presented.

In the case of determination of the refractive indices of the PMMA substrate foil (concerning the incident angle ②) we used a similar procedure: -17°55′ at 473 nm corresponds to refractive index 1.5009; -15°40′ at 633 nm corresponds to refractive index 1.4923 and -13°40′ at 1552 nm corresponds to refractive index 1.4819.

Optical losses of the planar waveguides were measured by a technique involving measurement of transmitted and scattered light intensity as a function of propagation distance along the waveguide [28]. Actually it follows losses of optical waveguides by scanning with a fiber optic probe and a photodetector down the length of a propagating streak to measure intensity of the light scattered from the surface of the guide. The optical fiber method is similar to a concept of a CCD camera used to measure decay of the propagating streak with the advantage that our approach does not need the camera that should have very uniform response sensitivity over the full array. With the scanning fiber method, only a small single-element silicon detector is used and spatial uniformity is not an issue [25], [29]. We measured optical losses by using He-Ne laser at 633 nm and the principle of the method is shown in Fig. 9.

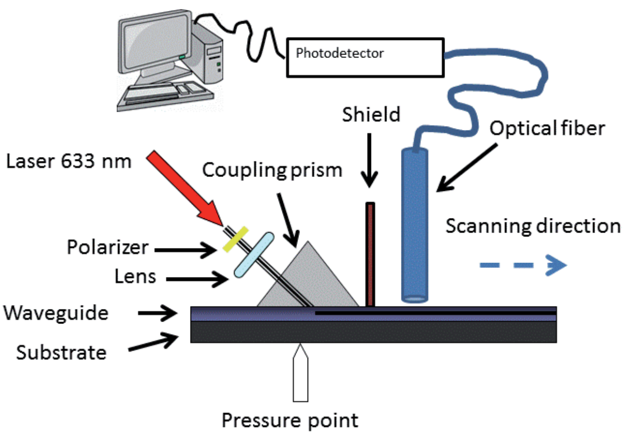

Fig. 9. Schematic view of the optical planar loss measurement.

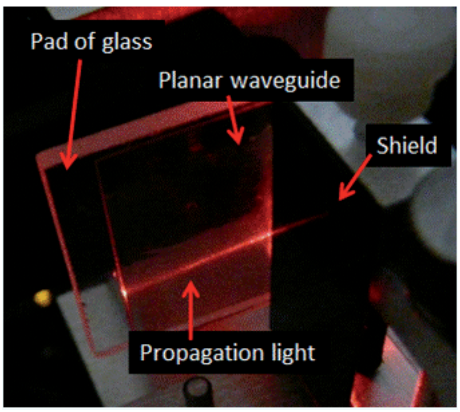

Fig. 10. Coupling of the optical signal (633 nm) into flexible polymer waveguides for optical loss measurements.

Fig. 10 shows an image of flexible waveguides supporting optical light at 633 nm. The flexible polymer sample must be fixed to a glass pad; otherwise the planar waveguides might bend, which would make achieving of quality optical contact difficult and thus worsen the coupling of the laser beam into the waveguide.

Optical loss measurements are given in Fig. 11 showing results for planar waveguide PMMA/Su8-5 in Fig. 11a and the results for PET/Su8-5 waveguide in Fig. 11b.

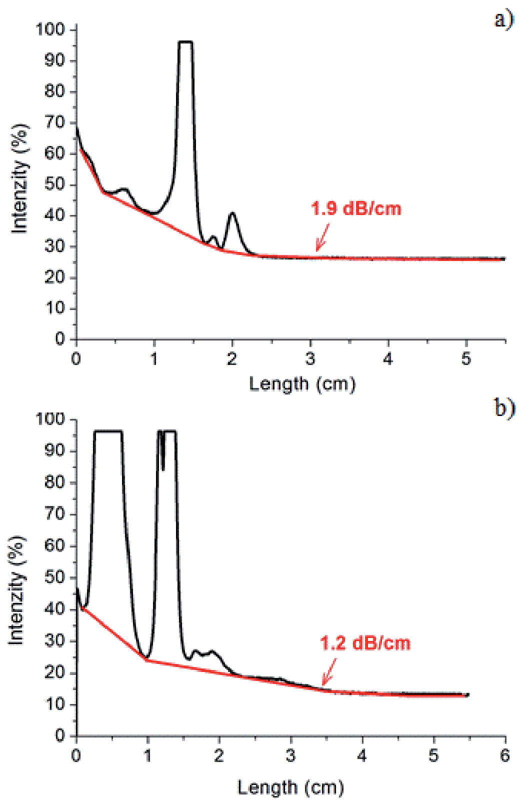

Fig. 11. Optical losses of the flexible waveguides for wavelength 633 nm a) PMMA/Su8-5, b) PET/Su8-5.

Our optical planar waveguides had optical losses lower than 2 dB·cm^{-1} with the best sample having optical losses as low as 1.2 dB·cm^{-1}. This value is similar to the values reported in [20], [22], [30] regarding to the facts that in [20] a single-mode waveguide Si/SiO_2/Su8/PMMA (1.36 for TE and 2.01 for TM modes) with the losses taken at longer (980 nm) wavelength is mentioned; the results in [22] (1.5 dB·cm^{-1} at 650 nm) are for a ridge waveguide and [30] (0.19 dB·cm^{-1} at 633 nm) concern much more demanding technology (proton beam writing).

5. Conclusion

We report about design, fabrication and properties of flexible polymer planar waveguides made of epoxy novolak resin (Su8) polymer as a core waveguide layer deposited on PMMA, CL400, or PET foil substrates.

Optical waveguiding properties of our planar waveguides samples were characterized by Metricon 2010 prism-coupler system for five wavelength (473, 633, 964, 1311 and 1552 nm) and optical losses were measured by collecting the scattered light using fiber scanning along the waveguide read by the Si photodetector at 633 nm. Our best sample had optical losses around 1.2 dB·cm^{-1}.

The main advantage of our samples is that they are deposited on flexible substrates which makes them suitable for advanced sophisticated interconnection devices. Next we are going to design and construct multimode flexible ridge waveguides based on the same principle.

Acknowledgements

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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 same department 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 photonics structures.

Pavla NEKVINDOVÁ was born in 1972 in Kolín, Czech Republic. She graduated from the Institute of Chemical Technology, Prague (ICTP) in 1999. Now she is the Assistant Professor at the ICTP giving lectures on general and inorganic chemistry. She has worked there continuously in materials chemistry research. She has a long-term experience with fabrication and characterization of optical waveguiding structures in single-crystalline and glass materials.

Petr HYPŠ was born in 1989 in Pelhřimov Czech Republic. He has studied at the Faculty of Electrical Engineering. Czech Technical University in Prague. In June 2013 he obtained a bachelor's degree in Communication, Multimedia and Electronics. Now his field of study is polymer photonics structures.

Oleksiy LYUTAKOV was born in 1982 in Kramatorsk, Ukraine. He studied at the Chemistry Faculty of Donetsk National University. He obtained the PhD degree at the Institute of Chemical Technology in 2009. At present he is working at the same institute at the Department of Solid State Engineering as a research fellow.

Vítězslav JEŘÁBEK was born in Prague in 1951. He received his M.Sc. and Ph.D. degrees in Microelectronics from the Czech Technical University in Prague in 1975 and 1987. He is currently an Associate Professor of Electronics and head of optoelectronic group at the Microelectronic Department, Czech Technical University in Prague.