Design, Fabrication and Measurement Polymethylmethacrylate Optical Waveguides Prepared by Modification of Surface Profile by Applying Electric Field

V. Prajzler[1], O. Lyutakov[2], J. Tuma[2], I. Huttel[2], J. Spirkova[2], V. Svorcik[2], V. Jerabek[1]
[1] Department of Microelectronics, Faculty of Electrical Engineering
Czech Technical University, Technicka 2, 166 27 Prague 6, Czech Republic
[2] Institute of Chemical Technology, Technicka 5, 166 28 Prague 6, Czech Republic
E-mail : xprajzlv@feld.cvut.cz, oleksiy1.lyutakov@vscht.cz, ivan.huttel@vscht.cz

Abstract:
In this paper, we describe results of our recent experiments on electric field preparation of the optical waveguides on PMMA films, their calculation and measurements. Planar PMMA films were prepared on Si/SiO_2 wafers and measured using waveguiding technique. Micro-sized patterns were created on thin PMMA films by the effect of external electric field, perpendicular to the film surface. Waveguiding properties of prepared structures were checked by fitting optical fibre connected to laser light source. Optical losses of the farbicated channel waveguides were measured by using the cut-back method at wavelength 650 nm and output field was obtained by beam propagation analyzer BP104IR. Properties of the PMMA layers were simulated by beam propagation method by using BeamProp module from RSoft software.

INTRODUCTION

Optical waveguides play a key role in optical communication networks and optical sensor systems [1, 2]. In backbone networks are mainly used single mode waveguides which permit transmission over longer distances with at higher bandwidths. There are also investigated optical communication networks and sensor systems which use multimode optical waveguides. For this systems are new distribution devices needed and for these devices are investigated new materials and fabrication processes. Up to now for optical components were usually used semiconductors, optical glass and optical crystals but new materials such as polymer are nowadays investigated as well [3-6] because semiconductors and other materials used for optical waveguides are expensive and technology processes for fabrication are rather complex.

Polymer materials for photonics applications are getting increasingly attractive due to low cost, high transparency in the visible and near-infrared spectra and easy fabrication process. There are a number of different polymers that can be considered for use in photonics applications. Optical polymers have been already engineered in many laboratories and some of them are nowadays available also commercially [7, 8]. In addition to the already investigated materials during last few years the attention has been paid also to developing new polymers and fabrication process for polymer layers offering, e.g., better time stability.

In this paper we describe results of design, fabrication and measurement of polymethylmethacrylate (PMMA) optical waveguides prepared by modification of surface profile by applying electric field.

EXPERIMET

Design of the polymer waveguides

To design and develop a good function optical channel waveguide one usually needs to start with the so-called planar waveguides. In this special case these are going to be the step-index planar slab waveguides. A typical thin-film waveguide structure consists of three dielectric regions, namely a substrate (n_s), a waveguide core (n_f) and a cover (n_a) layer (See Fig. 1).

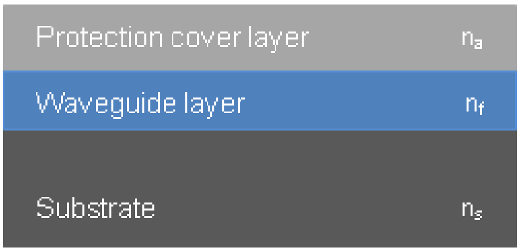

Fig. 1: Planar optical waveguide structure

The basic requirement for refractive indices of a planar slab waveguide is that the refractive index of the waveguiding layers has to be higher than refractive index of the used substrate and cover layer:

$$n_f > n_s,\ n_f > n_a \qquad (1)$$

For integrated optics it is desirable to fabricate all the components on silicon substrates. As the basic requirement for planar waveguides is to have the refractive index of waveguiding layers higher that refractive index of the used substrate, in the case of using silicon substrates it is inevitable to place between Si substrate and polymer waveguide a cladding layer. For this purpose we chose SiO_2

cladding layer due to easy fabrication process and suitable properties.
We calculated the thickness of the deposited PMMA waveguides film by using modification of dispersion equation [1]. The schema of the design of PMMA planar waveguide is given in Fig. 2 and this design was done assuming that the substrate refractive index $n_s = 1.46$ (substrate cladding layer SiO_2), and that of the waveguiding layers is $n_f = 1.49$ (PMMA waveguiding layer), while the cover layer is not applied $n_a = 1$ (cover layer is air). The designing was done for wavelength λ = 632.8 nm (He-Ne laser). The thickness of the PMMA layer is depicted for supporting 1 TE and TM mode and thickness of the SiO_2 cladding layer is design for the out-coupled energy of the evanescent wave would be less than 0.1 % [9].

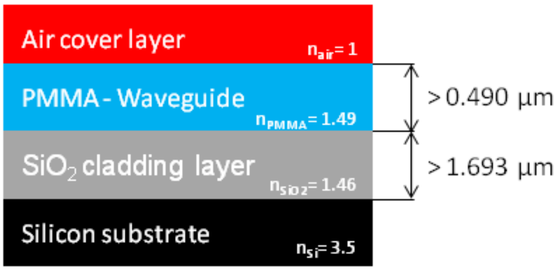

Fig. 2: Design of optical PMMA planar waveguides structure by modification dispersion equation (the thickness of the PMMA layer is the minimal one calculated to ensure guiding of one TE and one TM mode at the wavelength of 632.8 nm)

When the planar optical waveguide was suggested then the ridge polymer waveguides was design by using RSoft software using Beam Propagation Method (BPM). The design was done for the multimode waveguide with 50 µm width and 0.4 µm heights. It was assumed that the structure does not have a sharp edge. Therefore the structure has shape like Gaussian profile. The structure of the design ridge waveguide is depicted in Fig. 3.

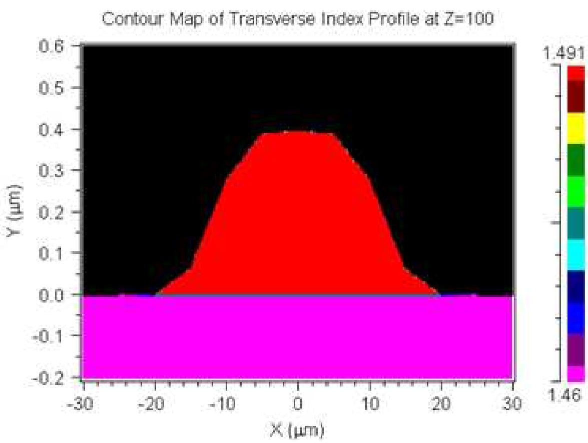

Fig. 3: Ridge PMMA waveguide structure design by beam propagation method using RSoft software (3D simulation).

In Fig. 4 there are given calculated field distribution for single mode (See Fig. 4a.) and for the first mode (See Fig. 4b) supported by prepared waveguide for operating wavelength 650 nm.

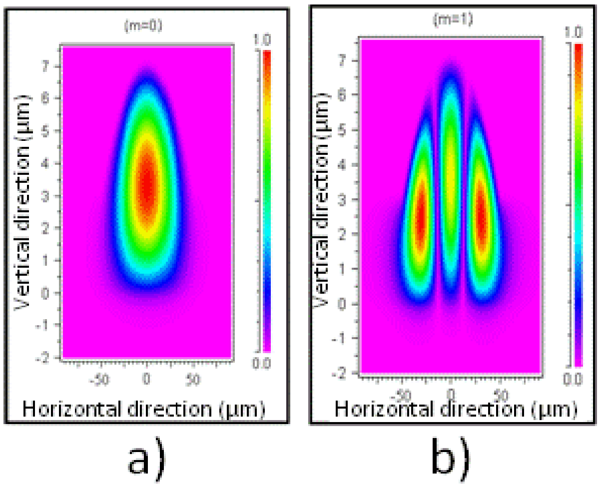

Fig. 4: Calculated light intensity distribution for a) fundamental mode, b) the first supported mode

Fabrication process

The present experiments were performed on PMMA of optical purity supplied by Goodfellow. The glass transition and fluid temperatures (T_g = 112°C, T_f = 275°C) of the polymer were determined by the standard calorimetric method using DSC 2920 technique. PMMA films, 0.5 µm thick, were spin-coated (1500 rpm) from 10.0 wt. % solution of PMMA in chloroform onto a Si/SiO_2 wafer (crystallographic orientation of Si (100), resistance 0.002 Ω cm, refractive index n = 3.505).
The schema of our experimental setup for waveguide fabrication is shown Fig. 5. The PMMA layers were deposited by using spin coating on Si/SiO_2 substrate and then exposed to electric field created between upper strip electrode (50 µm wide and several µm long). Strip electrode was prepared onto glass substrate using photolithography method. The distance from the upper electrode to the PMMA film was about 10 µm and the field intensities do not exceed a breakdown limit about $2.5 \cdot 10^6$ V/m. The whole assembly under electric field was heated in an oven to PMMA fluid temperature of 275±5°C. After exposure, the sample was allowed to cool down spontaneously to room temperature under the continued effect of the electric field. Creation of waveguide structure is more detailed explained in the work [10].

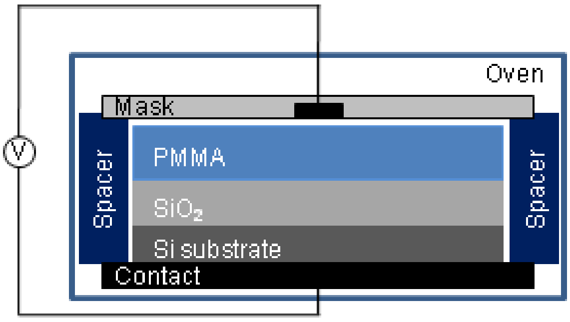

Fig. 5: The schema of the experimental setups

Measurement

Refractometer AvaSpec-2048-2 was used to measure refractive indices in the range from 350 to 750 nm. The measured values were evaluated by a computer programme Avantes. Waveguides properties of the planar waveguide samples were determined by mode spectroscopy (prism coupling method) by using He-Ne laser (632.8 nm). For optical coupling we used SF4 prism. The specially designed software (Planproof) was used for evaluation of the data obtained from the mode spectroscopy measurement.
The shape and properties of the resulting channel structures created on the PMMA layer were studied using optical microscope "Olympus". Profiles of the structures were measured by profile-meters Talystep Hommel 1000 and LEXT OLS 3000 microscope. The wave-guiding properties of the prepared linear structures were studied with semiconductor laser operating at 650 nm. Optical loss measurements were done using the cut-back method. The output light from the waveguides was measured by optical power meter Anritzu ML910B with MA9802A probe.

RESULTS AND DISCUSSION

In Fig. 6 there are given two examples of dependences of the refractive indices of the deposited layers on the wavelengths in the range between 350 and 750 nm. The first sample was fabricated by deposition of the 5% PMMA solution onto silicon substrate and by subsequent spinning at 700 rev./min. without the assistance of external electric field. The second sample was fabricated by the same deposition conditions but the layer was deposited in electric field.
Fig. 6 shows that PMMA layers fabricated in the electric field had higher values of refractive index than the layers fabricated without the influence of an electric field.

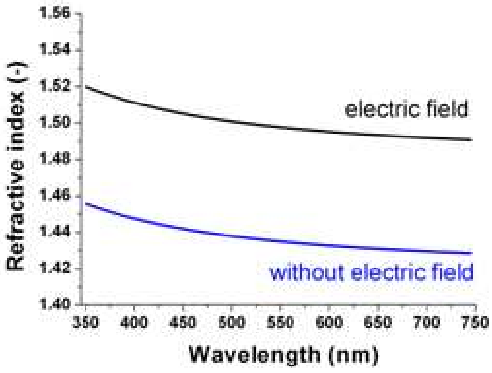

Fig. 6: Refractive index of the PMMA layers fabricated with and without applying electric field as measured at various wavelength

The waveguide properties were measured on planar optical waveguides deposited by spin coating on Si/SiO_2 substrates. We measured properties of thin PMMA layers deposited without the assistance of external electric field and also deposited by applying the assistance of external electric field (See Fig. 7 and Fig 8). Fig. 7 shows refractive index depth profiles for TE modes measured by using He-Ne laser operating at 632.8 nm of the layer fabricated using PMMA dissolved in dichlorethan (5 %) with rotation rate of 2 000 rev/min on Si/SiO_2 substrate.

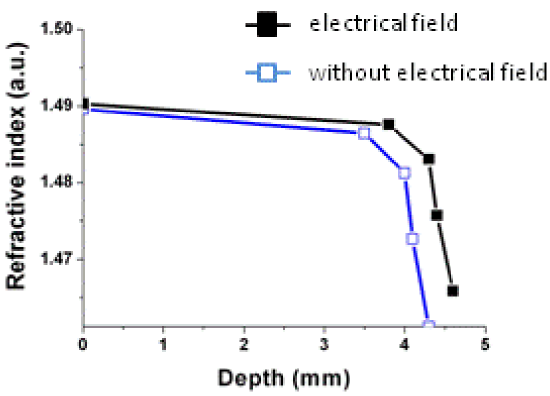

Fig. 7: Evaluation of the refractive index depth profile for TE modes at 632.8 nm of the sample fabricated by dissolving PMMA (5 %) in dichlorethan and deposited onto silica-on-silicon substrate

The PMMA layers fabricated in the electric field had higher values of refractive index than the layers fabricated without applying electric field. We also obtained the same dependence for the TM modes (See Fig. 8) [9].

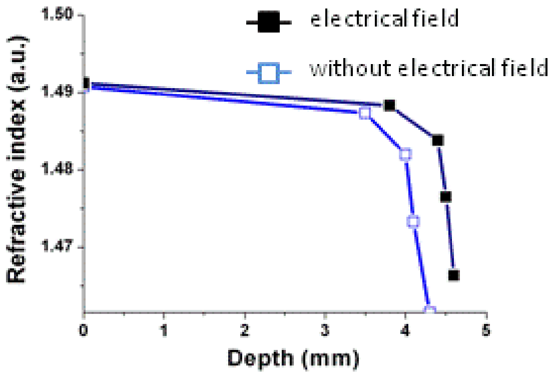

Fig. 8: Evaluation of the refractive index depth profile for TE modes at 632.8 nm of the sample fabricated by dissolving PMMA (5 %) in dichlorethan and deposited onto silica-on-silicon substrate

In Fig. 9 is shown fabricated optical waveguides obtained by using confocal microscope. Depicted structure was prepared by applying of electric field on initially flat PMMA film. Influence of electric field lead to polymer flow in the direction of electric field vector and redistribution of polymer material. Final structure presents vertically elongated channel. Rich interference pattern on the Fig. 7 corresponds with the thickness variation of structure created on the place affected by electric field.

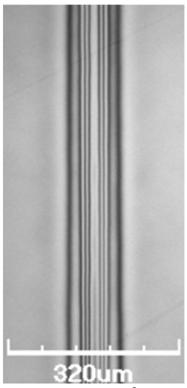

Fig. 9: Confocal microscope image of prepared structure

Results of measurements of geometry and refractive index were used for calculation of mod structure of prepared waveguide. It was found, that prepared structure can support several tens of modes. Calculated output optical field is given on the Fig. 10a. For comparison fig. 10b shows also measured output optical field.

To examine light-guiding properties of the PMMA Y linear structures was created by the present procedure. In Fig. 10a is shown photo of the chromium mask used for fabrication of the Y optical divider. In Fig. 10b is shown photo of the fabricated structures and in Fig. 10c is shown optical light from semiconductor laser operating at 650 nm was coupled by using optical fiber into PMMA polymer ridge waveguide fabricated onto Si/SiO_2 substrate.

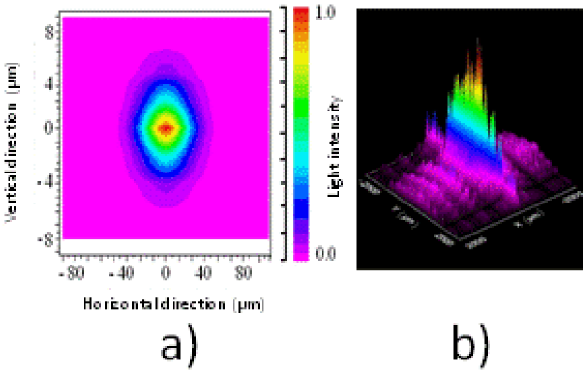

Fig. 10: Calculated and measured output optical field from the end of prepared rib waveguide

From the comparison of Y-splitter structure and light propagation it can be concluded, that prepared structure had waveguiding properties and light is restricted inside of structure.

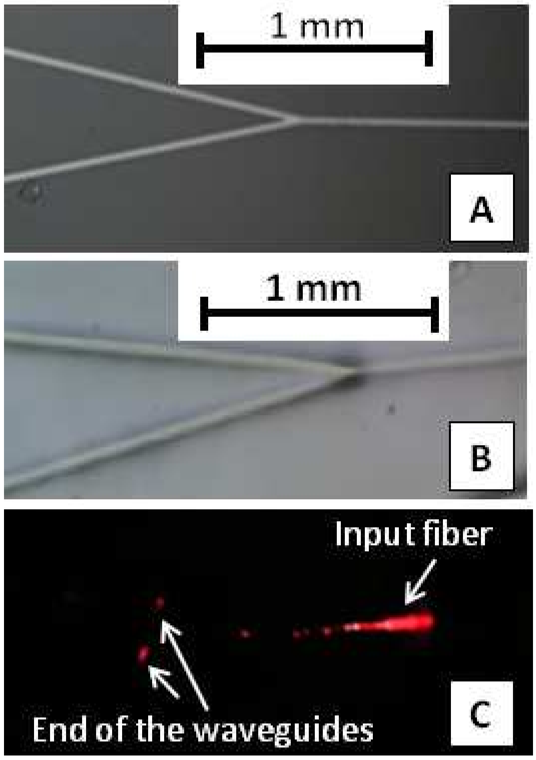

Fig. 11: a) – Photo of used mask with metal strip, b) – Photo of prepared Y-power splitter, c) - Binding and guiding of laser radiation (wavelength 630 nm) in Y channel waveguiding power splitter

The fabricated optical waveguides had optical losses around 0.85 dB/cm and oobtained optical losses are “acceptable” for potential usages for photonics applications.

The stability of the structure and its properties was checked in an experiment when the system was kept at 100°C for 100 hours and no measurable changes in the structure shape and properties were observed.

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CONCLUSION

The influence of the applied electric field on refractive indices of the deposited PMMA layers was studied. The PMMA layers fabricated in the electric field had higher values of refractive index than the layers fabricated without applying electric field. PMMA optical planar waveguides were fabricated by spin coating onto Si/SiO_2 substrates. The ridge optical polymer waveguides were created by the effect of locally limited electric field in thin PMMA films heated to fluid temperature. To examine light-guiding properties of the PMMA Y linear structures was created and the optical losses obtained for fabricated ridge waveguides was around 0.85 dB/cm at wavelength 650 nm.

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