Design, Fabrication and Properties of Rib Poly(methylmethacrylimide) Optical Waveguides

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Abstract. *We report about design, fabrication and properties of the polymer optical waveguides deposited on silica-on-silicon substrate. The design of the waveguides is based on a concept that geometric dimensions of the single mode polymer waveguide are determined by geometrical parameters of the silica layer. The design of the waveguides was schemed for 650 nm, 850 nm, 1310 nm and 1550 nm wavelength. The design of the presented planar waveguides was realized on the bases of modified dispersion equation while the ridge waveguides design was proposed following the Fischbeck concept. Both designs were refined applying RSoft software using beam propagation method. Proposed shapes of the waveguides were etched by standard photolithography process into the silica layers and polymer waveguide layers were subsequently deposited into the treated substrate by spin coating. Poly(methylmethacrylimide) was used as the waveguide core material and polymethylmethacrylate was used as a cover protection layer. Propagation optical loss measurements were done by using the cut-back method and the best samples had optical losses lower than 0.6 dB/cm at 650 nm, 1310 nm and 1550 nm.*

Keywords

Optical ridge waveguide, polymer, poly(methylmethacrylimide), photolithography.

1. Introduction

In recent years optical waveguides have played a key role in long haul optical communication networks and optical sensor systems. Due to the rapid widespread of the internet the communication devices in the Fiber-to-the-Home (FTTH) new photonics structures are strongly required [1]. FTTH devices consist of many optical and electrical elements. These elements are usually based on semiconductor or glass materials and accordingly the cost is little bit higher. Therefore many research groups are looking for fabrication of these elements with using new materials with comparable properties but easy fabrication process which allows fabrication of that structures by mass production and low cost.

Development of the FTTH will require also new type of the passive optical planar structures. For that new elements novel materials have to be developed. Such new materials can be polymers due to their suitable properties including sufficient time and temperature stability, high transparency from visible to infra red wavelengths, well-controlled refractive indices, low optical losses, easy fabrication process and also low cost. Most of the early work was focused to the polymethylmethacrylate (PMMA) as the waveguide material [2]. Nowadays lot of research groups examined a new type of polymer for photonics applications, for example Acrylate (AlliedSignal), Benzocyclobutene (Dow Chemical), Chloro-fluorinated polyimides (Samsung), Deuterated polysiloxane (NTT), Epoxy novolak resin (Micro Resist Technology), Fluorinated polyimide (Amoco), Halogenated acrylate, Polyetherimide (General Electric), Polycarbonate with CLD-1 chromophore (PacificWave), Polycarbonate (JDS Uniphase), Polyurethane (Lumera) and etc. [3-6]. Some of these polymers are also available commercially.

For our research we chose as a core waveguide material a new type of Poly(methylmethacrylimide) (PMMI). Chemical structure of PMMI is shown in Fig. 1 and our waveguide design was done for four wavelengths: 650 nm (used in laboratory experiments), 850 nm is used for low cost optical systems, and 1310 nm and 1550 nm are standard backbone telecommunication wavelengths.

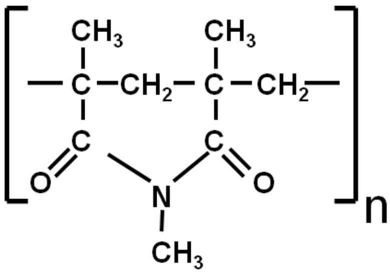


Fig. 1. Structure of the Poly(methylmethacrylimide).

2. Design of the Planar Waveguides

To design and develop optical rib waveguide one usually needs to start with the so-called planar waveguides. The simplest optical waveguide structure is the step index planar 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. Refractive index of the guiding layer n_f, must be higher than the refractive indices of the substrate n_s and cover layer n_c:

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

Due to easy integration process with other optical and electrical elements, it is highly desirable to deposit the optical waveguides onto silicon substrate but problem comes from very high value of the refractive index of silicon (around 3.49 at 1310 nm and 3.48 at 1550 nm). Therefore it is necessary to insert a separate buffer layer between silicon substrate and waveguides layer. Silica layer can be used as buffer layer n_s due to its easy fabrication process and suitable properties.

Before the actual proposal the silica buffer layer (SiO_2), optical waveguide layer (PMMI), and optical cover PMMA) protection layer were deposited on silicon substrate and the waveguide refractive indices were measured by ellipsometry in spectral range from 400 nm to 1600 nm (see Fig. 2). This figure shows that value of the refractive indices decreased with the increasing wavelengths. But in the case of the wavelengths of 1310 nm and 1550 nm the refractive indices have similar values.

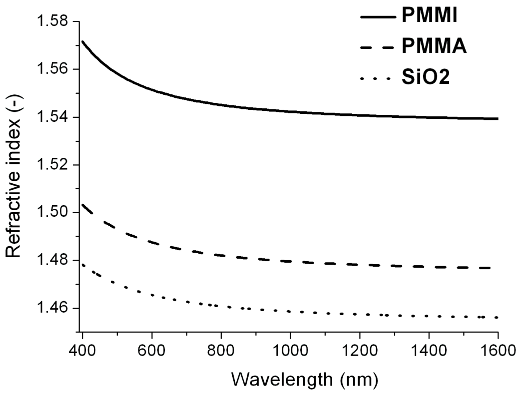


Fig. 2. Refractive indices of PMMI (poly(methylmethacrylimide)), PMMA (poly-methylmethacrylate) and SiO_2 layers measured by ellipsometry.

The obtained values were used for theoretical design to make the simulation accurate.

The structure of the designed optical planar waveguide is shown in Fig. 3. The thickness (h_f) of the core of the optical waveguides film was calculated by using modification of dispersion equation depicted in (2), number of guided modes (m) is determined from equation (3) [7]:

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

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

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

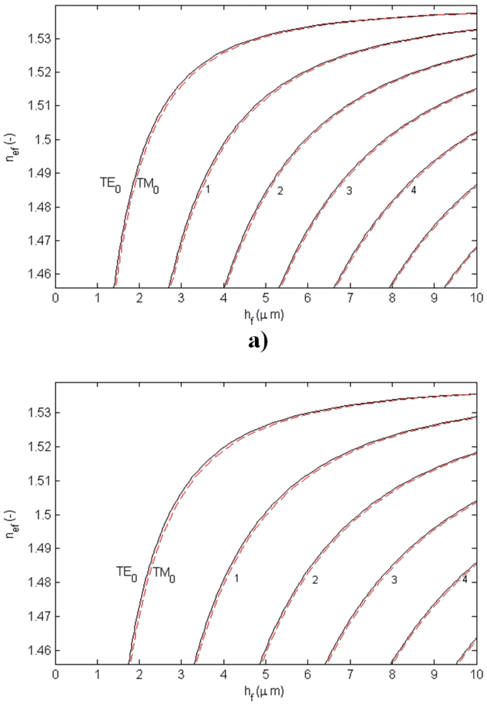
$$p = 1 \tag{4}$$

and for the TM mode

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

Fig. 3. Scheme of the PMMI optical planar waveguide.

The results of mode calculations performed for 1310 nm and 1550 nm for TE and TM for the waveguide structure described above are shown in Fig. 4.



a)

b)

Fig. 4. Mode calculation of the polymer planar waveguides. For operation wavelength a) 1310 nm, b) 1550 nm.

The single mode waveguides can be achieved for the thickness of the waveguide layer (h_f) 1.52 µm for 1310 nm and for thickness (h_f) 1.80 µm for 1550 nm wavelength. For bigger thickness (h_f) than 2.82 µm for 1310 nm or 3.35 µm for 1550 nm, the waveguides became multimode (for more details see Tab. 1).

To calculate the thickness of the silica buffer layer and PMMA protection layer one needs first to know the distribution of optical field of the guided waves. That distribution for particular modes can be determined from the relations below:

$$E_{yc,m} = e^{-w_m x}, \tag{6}$$

$$E_{yf,m} = \cos(u_m x) - \frac{w_m}{u_m}\sin(u_m x), \tag{7}$$

$$E_{ys,m} = \cos(u_m h_f) + \frac{w_m}{u_m}\sin(u_m h_f)e^{v_m(x+h_f)} \tag{8}$$

where u_m, v_m and w_m are called normalized propagation parameters and are defined as follows:

$$u_m = \sqrt{\left|k_f^2 - \beta_m^2\right|}, \tag{9}$$

$$v_m = \sqrt{\left|\beta_m^2 - k_s^2\right|}, \tag{10}$$

$$w_m = \sqrt{\left|\beta_m^2 - k_c^2\right|}. \tag{11}$$

k is propagation constant for given layers (c – cladding, f – waveguide film, s – buffer layer), β_m longitudinal propagation constant for particular guided modes and E – intensity of the electro-magnetic field.

To normalize intensity E to 1 we state the first derivation equal to zero and then we can calculate maximum of the function; this can be then utilized to determine the maximum of the electric field intensity within the waveguiding layer.

$$\frac{d}{dx}E_{yf,m} = 0 \rightarrow E_{\max}. \tag{12}$$

Using that value we can normalize the whole course of the distribution of the electric field intensity in the waveguide:

$$norm = \left|\cos(u_m E_{\max}) - \frac{w_m}{u_m}\sin(u_m E_{\max})\right|. \tag{13}$$

If we state the maximum of the above function equal to 1 and decrease of the energy was set to be between 0 and 1 (i.e., 0 to 100 %) then the calculation of the thickness of the adjacent layers is based on the intentional value of the decrease of the intensity of the electric field of that particular layer.

$$E_{yc\ norm,m} = \frac{e^{-w_m x}}{norm} = 0.01 \rightarrow x = h_c, \tag{14}$$

$$E_{ys\ norm,m} = \frac{\cos(u_m h_f) + \frac{w_m}{u_m}\sin(u_m h_f)e^{v_m(x+h_f)}}{norm} = 0.01 \rightarrow x = h_{SiO_2} \tag{15}$$

Parameters of the designed planar optical waveguides are listed in Tab. 1. The calculated thicknesses of the PMMI single mode planar waveguides and thicknesses of SiO_2 buffer and PMMA cover layer for TM modes are shown there. The thickness of the buffer SiO_2 layer and PMMA protection cover layer was set according to the calculated one, which ensures that the out-coupled energy of the evanescent wave would be less than 1 %.

Wavelength (nm)	mode	h_{SiO2} (µm)	h_f (µm)	h_c (µm)
650	TM_0 TM_1	0.94 1.33	0.75 1.39	1.26 1.71
850	TM_0 TM_1	1.23 1.74	0.98 1.83	1.65 2.25
1310	TM_0 TM_1	1.90 2.68	1.52 2.82	2.57 3.53
1550	TM_0 TM_1	2.27 3.19	1.80 3.35	3.03 4.14

Tab. 1. Calculated thicknesses of planar waveguide PMMI, SiO_2 buffer and PMMA cover layers for TM single mode.

The thicknesses of the SiO_2 buffer layer if bigger than 3.91 µm will work for all the wavelengths and the same is true for the thickness of the cover PMMA protection layer if it is thicker than 4.14 µm.

3. Design of the Rib Waveguides

The design of the presented rib optical waveguide is based upon modification of concept proposed by Fischbeck [8], which was deduced by Mercatili [9] and has already been implemented in semiconductor material system [10]. The structure of the designed rib waveguide is shown in Fig. 5.

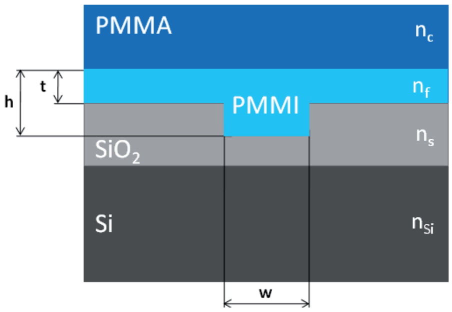


Fig. 5. Design of a rib optical waveguide.

Due to the Fischbeck concept we can use for the single mode rib waveguides simple approximation described as:

$$\frac{w}{h} \le 0.3 + \frac{\frac{t}{h}}{\sqrt{1-\left(\frac{t}{h}\right)^2}}. \tag{16}$$

where w is width and h is height of the waveguides and t is defined in Fig. 5. This equation is valid under the condition:

$$h < 2 \cdot t\,. \tag{17}$$

The width of the channel waveguide was determined by modification of the relation for calculation of critical thickness of a waveguiding layer (2). The width of the waveguide supporting one single mode then follows from:

$$w = \frac{\lambda_0}{2\sqrt{n_f^2 - n_s^2}}\,. \tag{18}$$

In Tab. 2 the calculated dimensions of the designed waveguides shown in Fig. 5 for the wavelengths of 650 nm, 850 nm, 1310 nm and 1550 nm are listed.

Wavelength (nm)	modes	t (µm)	w (µm)	h_f (µm)	h_{SiO2} (µm)	h_c (µm)
650	TE_{01}	0.74	0.65	1.35	0.97	1.23
	TM_{01}	0.75	0.65	1.36	0.94	1.26
850	TE_{01}	0.97	0.85	1.76	1.27	1.62
	TM_{01}	0.98	0.85	1.78	1.23	1.65
1310	TE_{01}	1.50	1.31	2.73	1.95	2.52
	TM_{01}	1.52	1.31	2.74	1.90	2.57
1550	TE_{01}	1.78	1.55	3.24	2.32	2.98
	TM_{01}	1.80	1.55	3.27	2.27	3.03

Tab. 2. Calculated thicknesses for rib waveguide PMMI, SiO_2 buffer and PMMA cover layer.

The design of the waveguide was also specified by Beam Propagation Method using BeamProp software, which is part of the RSoft software [11]. The calculated fundamental mode of a single mode rib waveguides operating at 650 nm is shown in Fig. 6a, that one operating at 850 nm is shown in Fig. 6b, for operating wavelength 1310 nm it is shown in Fig. 6c and that for operating wavelength 1550 nm is shown in Fig. 6d. Calculated fundamental modes are approximately 1.573 at 650 nm, 1.564 at 850 nm, 1.557 at 1310 nm and 1.557 at 1550 nm. From the simulations it follows that refractive indices for both 1310 and 1550 nm have the same value.

4. Fabrication of the Waveguides

The experiments were performed on PMMI (8813) polymer supplied by Evonik Industries AG. Fabrication process of preparation of silica-on-silicon substrates is illustrated in Figs. 7a-f and fabrication process of ENR polymer optical channel waveguides is shown in Fig. 7g step by step.

The silicon substrates with 7µm silica layer were used for fabrication of polymer ridge waveguides. First, silica layer was deposited by using HiPOX on silicon substrate (ON Semiconductor Roznov pod Radhostem, Fig. 7a). Than photoresist S1813 was deposited by using spin coating onto silica layer (Fig. 7b), then so called soft baking was done at 90°C for 3 min. After that photolithography by PERKIN-ELMER 300 HT Micralign was performed (Fig. 7c) followed with dipping into MF322 developer (Fig. 7d). Hard baking at 110°C for 3 min was the next step. Then SiO_2 etching was done by using POL solution at temperature 23°C (Fig. 7e). Finally photoresist S1813 was removed by using the solution of hydrogen peroxide and sulfuric acid (Fig. 7f).

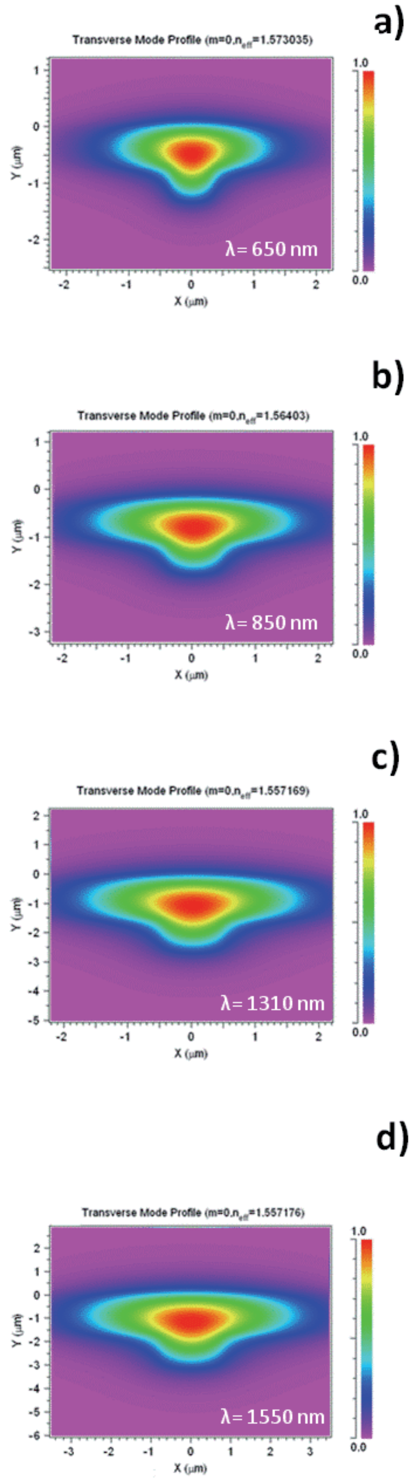


Fig. 6. Calculated modes of a single mode rib optical waveguide for various wavelengths a) λ= 650 nm, b) λ= 850 nm, c) λ=1310 nm, d) λ= 1550 nm.

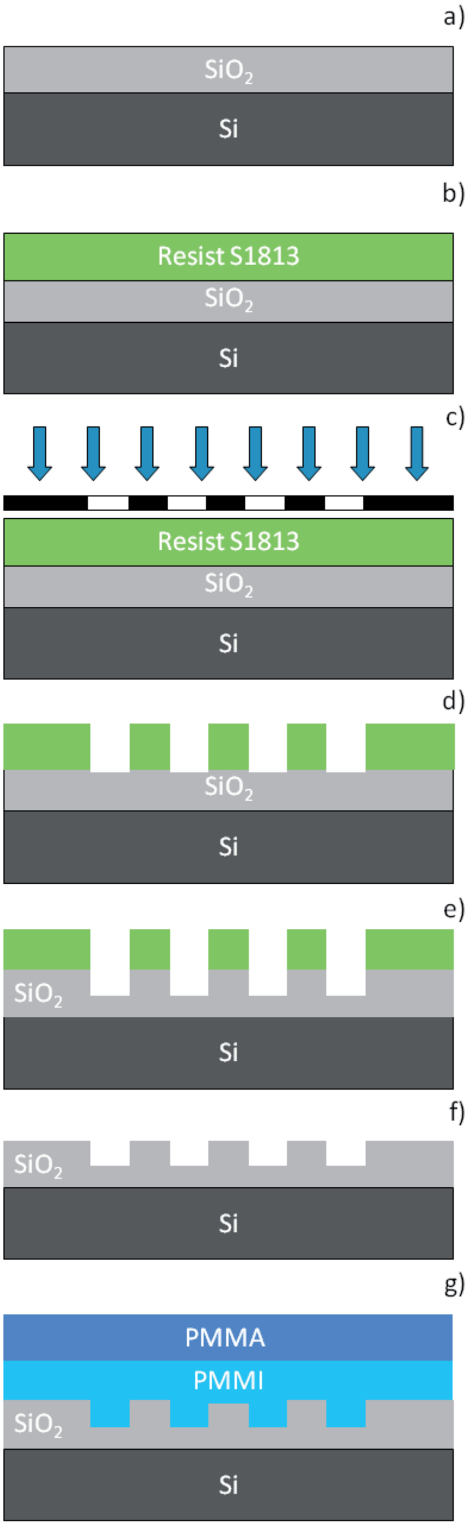


Fig. 7. Fabrication process of Si/SiO$_2$ substrate: a) deposition of the silica layer, b) deposition of the resist S1813, c) photolithography process, d) resist etching, e) etching of the silica layer, f) resist removing, g) deposition of PMMI optical waveguides and PMMA protection cover layer.

After the silica layer substrate was trimmed to the “waveguide” shape (Fig. 7f) the PMMI waveguiding layer and the PMMA as protecting cover layer was deposited by spin-coating (Fig. 7g).

5. Results

Transmission measurements were performed using a UV-VIS-NIR Spectrometer (UV-3600 Shimadzu) in the spectral range from 300 to 1600 nm (Fig. 8). The spectrum suggests that the polymer has absorption peaks in the near infrared wavelength region, and these bands can be attributed to the vibrational overtones of C–H bonds. The intrinsic bulk polymer has low absorption in the visible wavelength regions; however, at 1310 nm and 1550 nm the absorption is rather higher.

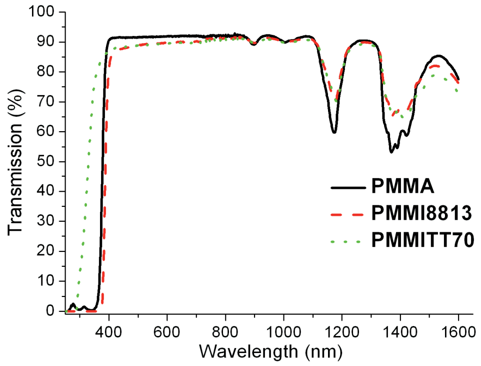


Fig. 8. Transmission spectra of PMMI and PMMA layers.

Waveguiding properties of our ENR planar waveguides were examined by using Metricon 2010 prism-coupler system. This apparatus works on the principle of the dark mode spectroscopy [12] and the measurement done at 632.8 nm, 1311 nm and 1552 nm (Fig. 8) proved that planar waveguides have good waveguiding properties at all three wavelengths.

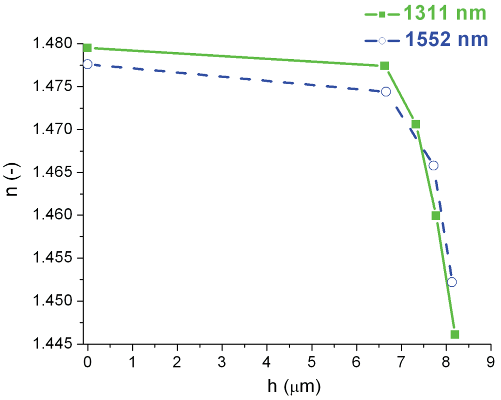


Fig. 9. Evaluation of the refractive index depth profile of PMMI polymer waveguide deposited on Si/SiO$_2$ substrate (TM modes).

The results shown in Fig. 9 confirmed the expected step-like character of the refractive index depth profiles of the waveguides. They also showed small decrease of the refractive index values with the increasing wavelengths (see also Fig. 2).

Surface quality of the fabricated rib optical waveguides was checked using optical microscope Olympus DX60 (Fig. 10).

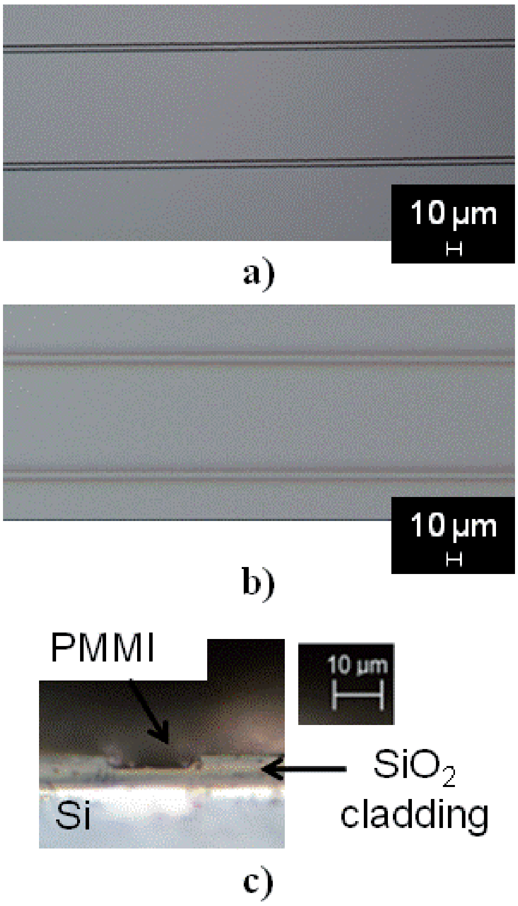


Fig. 10. PMMI rib waveguides with the PMMA over cladding layer a) face look and b) edge (side) look.

Fig. 10a shows an image of two etched lines in silica on silicon substrate and in Fig. 10b PMMI rib optical channel waveguides fabricated on silica on silicon substrate without PMMA cover protection layer are shown. Fig.10c shows the edge view. Fig. 10 reveals that the waveguides had good optical quality with no defects.

Optical loss measurements were done using the cut-back method [13]. The principle of the method is shown in Fig. 11 and the optical losses were calculated from equation (19).

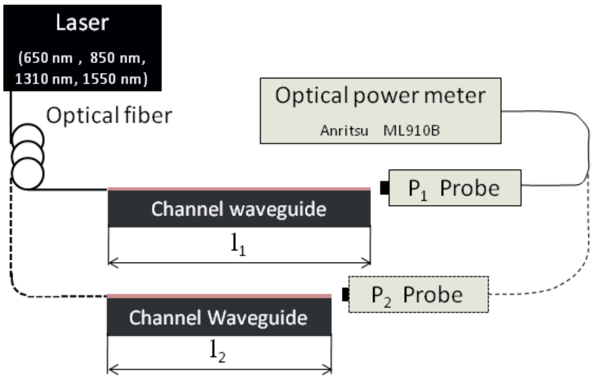


Fig. 11. Evaluation of the refractive index depth profile of PMMI polymer waveguide deposited on Si/SiO$_2$ substrate (TM modes).

$$\alpha(dB\cdot cm^{-1})=\frac{10\cdot\log\dfrac{P_1(W)}{P_2(W)}}{l_1-l_2(cm)} \tag{19}$$

where P_1 is output optical power measured on whole length of the waveguide l_1, P_2 is output optical power obtained after breaking the waveguide, l_2 is the length of the broken part of the optical waveguide. (For more details see Fig. 11.) For optical loss measurements we used semiconductor lasers operating at 650 nm, 850 nm, 1310 nm and 1550 nm. The output light from the waveguides was measured by optical powermeter Anritsu ML910B with MA9802A (650 nm) or MA9302A (850 nm, 1310 nm and 1550 nm) probes. Examining of light-guiding properties of the PMMA linear structures created by the above mentioned procedure is shown in Fig. 12.

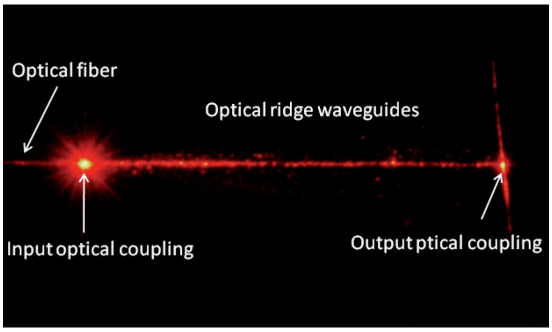


Fig. 12. Coupling of the optical signal (650 nm) into PMMI ridge waveguides for optical loss measurements using the cut-back method.

The fabricated optical channel waveguides had optical losses lower than 1.1 dB/cm. The best samples had optical losses around than 0.56 dB/cm at 650 nm, 1.09 dB/cm at 850 nm, 0.53 dB/cm at 1310 nm and 0.30 dB/cm at 1550 nm.

6. Conclusion

We report about the design, fabrication and properties of the polymer PMMI optical rib waveguides deposited on silica-on-silicon substrate. The design of the presented waveguide is based upon modification of the concept proposed by Fischbeck, which is based on the idea that geometric dimension of the single mode polymer waveguide is specified by silica layer. This procedure will allow for fabrication of polymer waveguides even if the waveguiding layer is not actually a resist, because the resultant shape of the waveguide is actually determined by the silica buffer layer already deposited on silicon substrate. Theoretical design of the waveguide was done on the bases of the beam propagation method via the RSoft software.

Optical waveguiding properties of our PMMI planar waveguides samples were confirmed by using Metricon 2010 prism-coupler system and gave the refractive index values 1.489 at 632.8 nm, 1.479 at 1311 nm and 1.477 at 1552 nm. The measurement also showed a good quality of the waveguides. Optical loss measurements were done using the cut-back method and the samples had optical losses lower than 1.1 dB/cm. The best samples have optical losses 0.53 dB/cm at 1310 nm and 0.25 dB/cm at 1550 nm.

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