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Designed and Fabrication of ENR Polymer Rib Optical Waveguides

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Abstract:
We report about design, fabrication and properties of the Epoxy Novolak Resin (ENR) polymer rib optical waveguides. Polymer waveguides were fabricated on silicon substrate with silica buffer layer and Epoxy novolak resin was used as the waveguide core material. Polymethylmethacrylate was used as a cover protection layer. The optical waveguides were designed by using software RSOFT using Beam propagation method and the minimum (critical) waveguiding thicknesses of the deposited layers were calculated using dispersion equation. Polymer layers were fabricated by spin coating and optical waveguides were form by using standard photolithography process. Propagation optical loss measurements were carried at 650 nm and 1310 nm using the cut-back method and the best samples had optical losses lower than 1.0 dB/cm at 650 nm and 0.6 dB/cm at 1310 nm.

INTRODUCTION

Optical waveguides are fundamental elements used in optical communication systems and advanced optical waveguides have been developed during last decades due to new options for photonics applications [1]. Through the years were investigated lot of type of optical waveguides using many different materials such as optical glasses, some dielectric crystals (e.g. $LiNbO_3$, $LiTaO_3$) or semiconductors (Si, GaAs, InP, GaAlAs, GaAsP, InAsSb, GaN and GaInN) [2-4]. For fabrication optical planar waveguides were also used many different fabrication techniques for example vacuum deposition methods (vacuum evaporation and sputtering), diffusion techniques, ion exchange, ion implantation etc. These materials and applied techniques for fabrication optical waveguides are expensive and sometimes too complicated.

However, these disadvantages can be overcome by using new polymer materials. Polymers are low cost and process of optical waveguides deposition is easy. Polymers are also versatile materials with good optical and mechanical properties such as high transparency in the visible and near-infrared spectra and well-controlled refractive indices [5, 6].

In this paper we present designing, fabrication and properties of optical polymer waveguides deposited on silica on silicon substrate. Epoxy Novolak Resin (ENR) polymer was chosen as core waveguides material for its excellent mechanical, optical properties and easy fabrication process [7, 8].

DESIGN OF THE WAVEGUIDES

A typical optical waveguide structure consists of three dielectric regions, namely a substrate (buffer layer) (n_s), a waveguide core (n_f) and a cover (n_a) layer. The basic requirement for refractive indices of a planar slab waveguide is that the refractive index of waveguiding layers has to be higher than refractive index of the used substrate (see equation 1):

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

In the case of using silicon substrates it is inevitable to place between Si substrate and polymer waveguide a buffer layer. Therefore we fabricated SiO_2, and polymer layers (ENR and PMMA) on silicon substrate and investigated their refractive indices. For this purpose we measured reflectance spectra by using Refraktometr Avaspec 2048 in spectral range from 300 nm to 750 nm (See Fig.1.) and we calculated refractive index by using Spektra3 software.

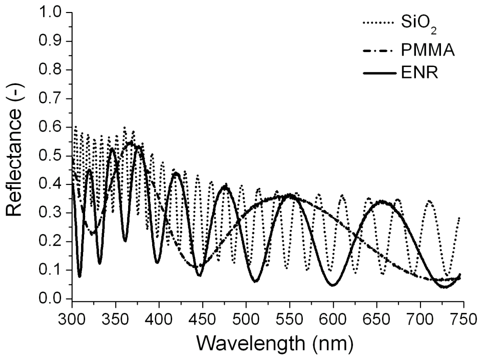

Fig. 1: Reflectance spectra of SiO_2, PMMA and ENR layers

Obtained data are presented in Fig. 2 and show that the refractive indices generally decreased with increasing wavelength. It is also shown that the refractive index of ENR is higher comparing with that of PMMA and SiO_2 layers. Therefore the condition for the waveguiding effect illustrated with equation 1 is fulfilled. These obtained data were also used for the theoretical design of optical rib waveguides simulations mentioned below.

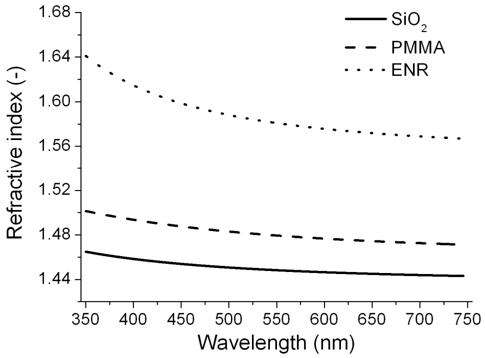

Fig. 2: Refractive indices of SiO_2, PMMA and ENR layers

The thickness of the core optical waveguides film was calculated by using modification dispersion equation depicted in (2), number of guided modes is described by equation (3), where equations (4) and (5) refer to the TE and TM modes [9].

$$h_m = \frac{\lambda_0}{2\pi\sqrt{n_f^2 - n_s^2}}\left\{m\pi + arctg\left[p_{13}\sqrt{\frac{n_s^2 - n_a^2}{n_f^2 - n_s^2}}\right]\right\} \tag{2}$$

$$m = Int\left\{\frac{2}{\lambda_0}h\sqrt{n_f^2 - n_s^2} - \frac{1}{\pi}arctg\left[p_{13}\sqrt{\frac{n_s^2 - n_a^2}{n_f^2 - n_s^2}}\right]\right\} \tag{3}$$

where p_{13} for TE mode is

$$p_{13} = 1 \tag{4}$$

and for TM mode it is

$$p_{13} = \left(\frac{n_f}{n_s}\right)^2 \tag{5}$$

The thickness of the buffer SiO_2 layer and Polymethylmethacrylate (PMMA) protection cover layer was set according to calculated one, which ensures that the out-coupled energy of the evanescent wave would be less than 0.1 %. Design of the waveguides was done for two wavelengths. For 632.8 nm due to laboratory purpose (He-Ne laser) and 1310 nm due to this wavelength is a standard telecommunication wavelength.

In Tab. 1 there are depicted calculated thicknesses for waveguides shown in Fig. 3a for optical waveguides supporting 5 modes for operating wavelength at 632.8 nm (SiO_2 buffer layer - h_2, PMMA protection cover layer - h_3, ENR waveguiding layer - h_1).

Tab. 1: Calculated waveguide thicknesses supposing that $n_s = 1.46$ (SiO_2), $n_f = 1.59$ (ENR), $n_a = 1.49$ (PMMA) of the designed ENR planar waveguides operating at 632.8 nm supposing refractive indices in Fig. 3a.

modes	h_3 (μm)	h_1 (μm)	w (μm)	h_2 (μm)
0	1.29	0.57	1.14	1.13
1	1.53	1.08	1.71	1.28
2	1.66	1.58	2.28	1.35
3	2.54	2.08	2.85	1.72
4	3.11	2.59	3.42	1.87

The design of the waveguide was done by RSoft software using Beam Propagation Method (BPM). The structure of the designed waveguide is shown in Fig. 3a and the calculated fundamental mode of a single mode channel waveguides operating at 632.8 nm is shown in Fig. 3b. According to the design of the waveguides the minimum thickness the ENR layer that would guide one mode must be bigger than 570 nm and the width have to be larger than 1140 nm (632.8 nm). This calculation proved that effective refractive index for fundamental mode is approximately 1.54.

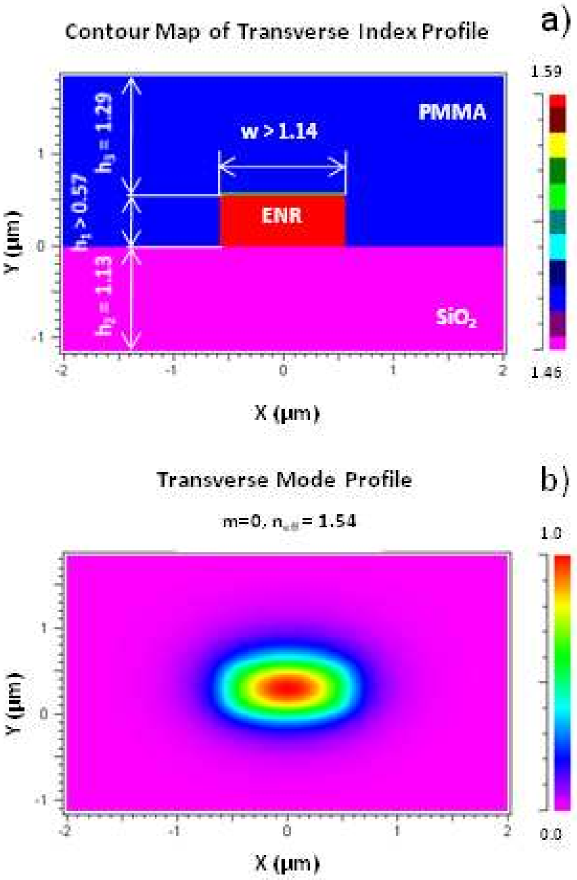

Fig. 3: a) Design of the ENR optical waveguide operating at 632.8 nm supporting one mode and b) BPM calculation of fundamental mode of a single mode rib waveguide

In Tab. 2 there are depicted calculated thicknesses waveguides for operating waveguides at 1310 nm.

Tab. 2: Calculated waveguide thicknesses supposing that $n_s = 1.46$ (SiO_2), $n_f = 1.59$ (ENR), $n_a = 1.49$ (PMMA) of the designed ENR planar waveguides operating at 1310 nm supposing refractive indices in Fig. 4a.

modes	h_3 (μm)	h_1 (μm)	w (μm)	h_2 (μm)
0	3.55	1.19	2.36	2.86
1	4.17	2.23	3.54	3.16
2	4.82	3.27	4.72	3.41
3	5.52	4.31	5.90	3.64
4	6.54	5.35	7.08	3.89

The structure of designed waveguide is shown in Fig. 4a and the calculated fundamental mode is shown in Fig. 4b. According to the design of the waveguides the minimum thickness of the ENR layer that would guide one mode must be bigger than 1190 nm and the width have to be larger than 2360 nm. This calculation proved that effective refractive index for fundamental mode is approximately 1.54.

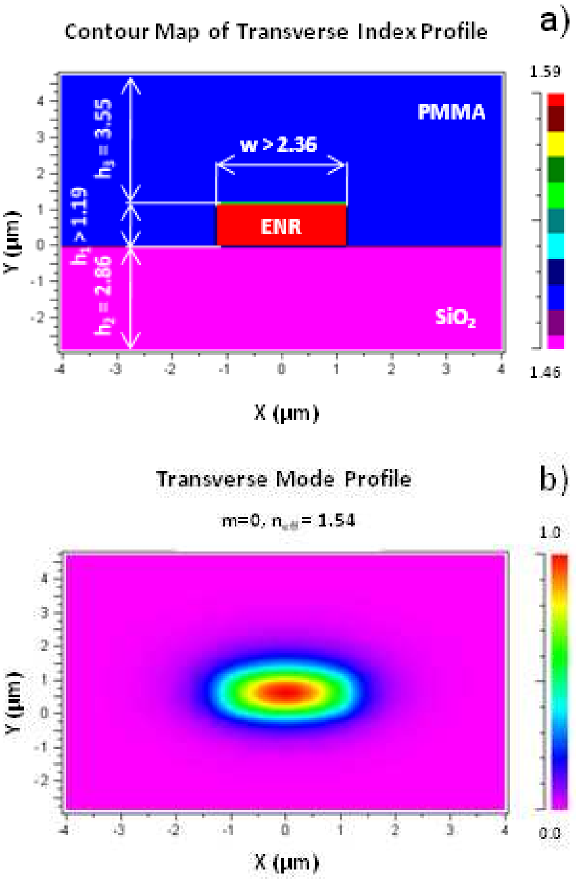

Fig. 4: a) Design of the ENR optical waveguide operating at 1310 nm supporting one mode and b) BPM calculation of fundamental mode of a single mode rib waveguide

FABRICATION OF THE OPTICAL WAVEGUIDES

The present experiments were performed on Epoxy Novolak Resin (ENR) polymer supplied by Micro Resist Technology GmbH. Chemical structure of ENR polymer is shown in Fig. 5.

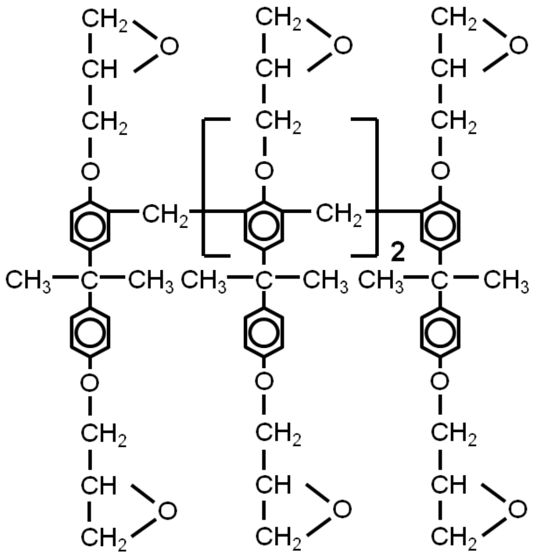

Fig. 5: Structure of the Epoxy Novolak Resin polymer

The ENR polymer layers were fabricated by spin coating on silica on silicon substrates and the channel waveguides were etched by standard photolithography using MR-DEV 600 developer. PMMA layer was used as protection cover layer. For that small pieces of PMMA (Goodfellow) were left to dissolve in chloroform for few days and the solution was then spin coated onto the waveguide layers.

Fabrication process of ENR polymer optical channel waveguides is shown in Fig. 6 step by step. First, before the deposition the Si/SiO_2 substrates were cleaned by standard cleaning procedure Fig.6(a). Then core layer was deposited by spin coating with rotation rate 1000 rev./min and deposition time 6 min Fig.6(b). After that in order to obtain a good adhesion, the ENR layer was dried for 45 min at temperature of 90°C, than the samples were let to harden by UV light over the photolithography mask. The following step was post-baking at 90°C for 20 min. Fig.6(c). The post-baked samples were dipped for 15 seconds into MR-DEV 600 developer Fig.6(d) and consequently heated again for 30 min at 90°C. Finally PMMA cover layer were deposited onto the samples by spin coating (Fig.6(e)).

The modeling described above gave us a basic conception on the dimensions of the thought waveguides. However, the lithographic masks needed for the fabrication of the real waveguiding structures did not meet precisely the requirements coming from the theoretical design, so that the properties of the resultant waveguides were expected slightly different from the calculated ones.

Thus, the final channel waveguides were approximately 2 μm high, 10 μm wide and 25 mm long.

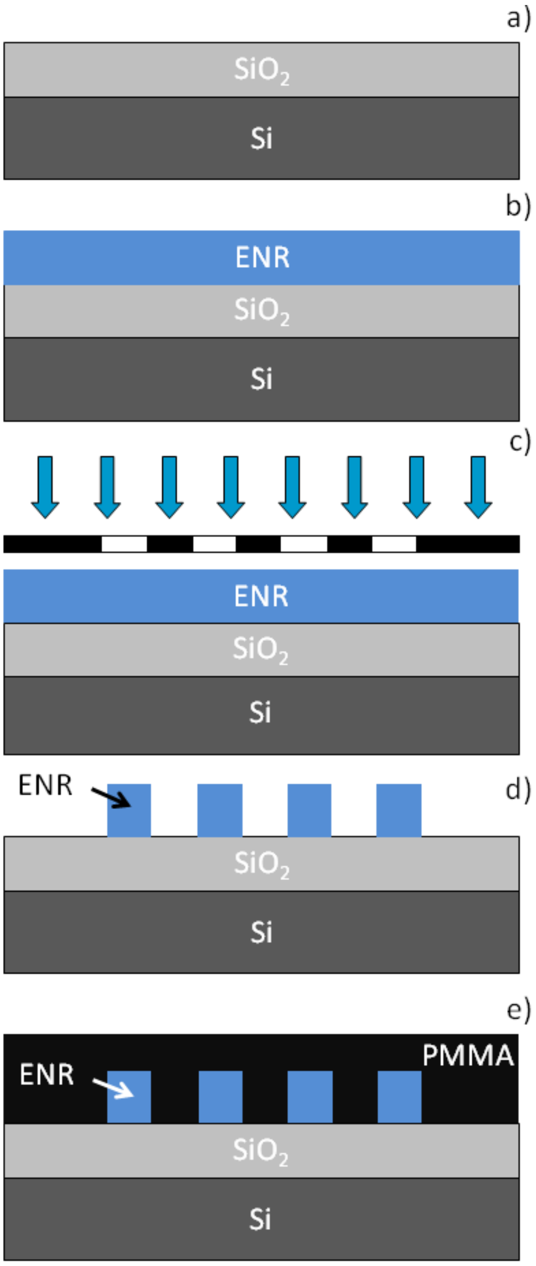

Fig. 6: Fabrication process of ENR polymer optical waveguides

PROPERITES OF THE WAVEGUIDES

Surface quality of the fabricated optical waveguides was examined using optical microscope (Olympus DX60). Fig.7 shows an image of five ENR rib optical channel waveguides fabricated on silica on silicon substrate with PMMA cover protection layer.

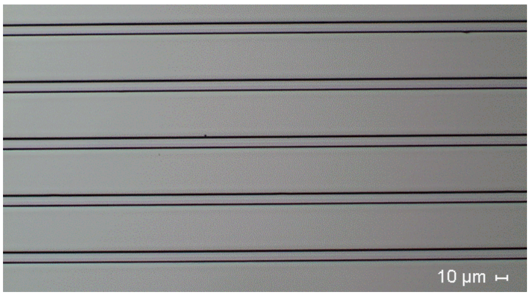

Fig. 7: ENR waveguides with the PMMA over cladding layer

Propagation optical loss measurements were carried at 650 nm and 1310 nm using the cut-back method. The principle of the method is shown in Fig. 5 and the optical losses were calculated by equation (6).

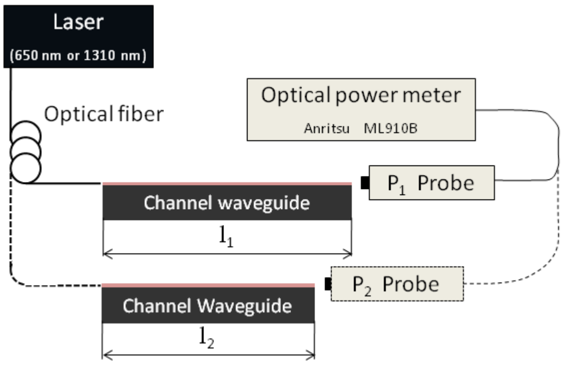

Fig. 8: ENR waveguides with the PMMA over cladding layer

$$\alpha(dB \cdot cm^{-1}) = \frac{10 \cdot \log \dfrac{P_2(W)}{P_1(W)}}{l_1 - l_2(cm)} \qquad (6)$$

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 of the waveguide, where l$_2$ is length of the break of the optical waveguide. For more details see Fig. 8.

For optical loss measurements we used semiconductor lasers operating at 650 nm and 1310 nm. The output light from the waveguides was measured by optical powermeter Anritzu ML910B with MA9802A (650 nm) or MA9302A (1310 nm) probes.

The fabricated optical channel waveguides had optical losses lower than 3.0 dB/cm. The best samples had optical losses lower than 0.6 dB/cm at both wavelength 650 nm and 1310 nm.

CONCLUSION

We report about design, fabrication and properties of a new polymer optical waveguides. The planar waveguides were designed using modified dispersion equation while the design of the channel waveguides was done on the base of the beam propagation methods using RSoft software.

The experimental samples were then fabricated by spin coating method on silica on silicon substrates. As waveguide core material was chosen new type polymer Epoxy Novolak Resin polymer and the channel waveguides were etched by standard photolithography process. Finally, Polymethyl-methacrylate polymer was used as cover protection layer.

Propagation optical loss measurements were done using the cut-back method. Best samples had optical losses 0.56 dB/cm at 650 nm and 0.55 dB/cm at 1310 nm.

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