BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 59, No. 4, 2011
DOI: 10.2478/v10175-011-0047-5

Differential interference in a polymer waveguide

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Abstract. The paper presents the results of investigations concerning the measurement of the refractive index and the thickness of planar waveguide structures, obtained by photo polymerization of the polymer SU8. In the paper the mode sensitivity has been calculated as a function of the thickness in a single-mode structure. The thickness of the layer has been determined in the case when the interferometer is most sensitive to changes of the refractive index.

Key words: planar waveguides, interferometers, integrated optical sensors, difference interferometer.

1. Introduction

For the purpose of constructing optical planar sensors various techniques are applied, e.g. ion exchange, plasma-enhanced chemical vapour deposition (PECVD) and spin coating in the case of SU8-polymer waveguides [1–11].

SU8 is a polymer based on epoxy resin, developed in 1989 by IBM. Thanks to its properties it is now one of the most attractive materials used in the optical planar technology. SU8 is rather cheap and displays a high thermal and chemical stability as well as good resistance to mechanical damages and an unusual transparency. The wide range of products ready for use, offered by manufacturers of SU8 (MicroChem and Gersteltec Sari) in the course of one technological process layers can be obtained with a thickness of 0.2 μm up to 2 mm.

Such good properties of the polymer SU8 are due to its unique structure. The chief component is epoxy resin, called EPON®, consisting of SU monomers, and responsible for its mechanical properties and adhesion to the substrate. Another also very important component is photoinitiatis, viz. Lewis acid, responsible for the initiation of cross-linking, in the course of which an epoxy ring is opened [12]. The last component is a solvent, which is indispensable for warranting an adequate viscosity of the mixture.

So far SU8 has been applied mainly in the technologies MEMS and MOEMS, being highly resistant and very sensitive photoresist processes involving selective plasma digestion, but also in photolithography. Because of its very good optical properties [13, 14] it is utilized in the production of optical sensors operating in the interferometer system [15].

2. Fabrication

For the purpose of investigations a series of planar waveguide structures was prepared for the SU8 polymer of varying thicknesses. As a substrate soda-lime glass plates were used, previously washed and rinsed in nitric acid, acetic acid and ammonia liquor. The polymer SU8 is characterized by a weak adhesion to glass substrates [15]; therefore, in order to avoid damages of the structure in the course of depositing the polymer, the entire procedure of washing was accomplished in a laminar cell with air filtration, holding it for 5 minutes at a temperature of 130°C. Upon the substrate SU8 was deposited by spin coating in a centrifuge from the firm Rein Raum Technik Lanz, specially adapted for this purpose. The proper amount of SU8 was batched by means of an automatic feeder with its nozzle directed towards the immovable substrate mounted in the centrifuge. The thickness of the layers depended on the velocity of gyration of the centrifuge.

In order to improve the homogeneity of the coating, each plate was after the deposition of SU8 cooled down for five minutes to room temperature (relax time). Next each structure was subjected to initial soft baking on a hot plate provided with a micro processing programmer. At this stage controlling the temperature is of crucial importance for the whole process, and just therefore its precise measurement is indispensable.

Each structure, irrespective of the thickness of the waveguide SU8 layer, was preheated from room temperature to 65°C with a surplus of 2°C [15], after which the temperature of 65°C was maintained for 10 minutes. The following step was heating up from 65°C to 95°C with a surplus of 2°C/min., which latter temperature was maintained for 60 minutes.

After the structure had cooled down to about 30°C its exposure was started. For this purpose an irradiator MJB3 produced by the firm Karl Suss was used. The batching of UV radiation by means of a mercury discharge lamp (OSRAM HBO 250 W) was adjusted individually for each thickness of the SU8 layer. The parameters of irradiation have been gathered in Table 1. The irradiation was followed by post-exposure baking, similarly as in the case of preliminary soft baking.

The final stage of generation was the development of the structure by means of the developer PGME [15]. The time of the development can also be gathered from Table 1. After their development the structure was washed with isopropanol and dried at room temperature.

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Table 1
Technological conditions of the deposition of SU8 layers

Spin speed [rpm]	Pre-baking	Relax time [min.]	Exposure time [s]	UV dose [mJ/cm^2]	Post-exposure baking	Developing time [s]
2000	25°C – 65°C/20 min. 65°C/6 min, 65°C – 95°C/15 min, 95°C – 40 min.	5	42	235	25°C – 65°C/20 min. 65°C/6 min, 65°C – 95°C/15 min, 95°C – 22 min.	35
3000	25°C – 65°C/20 min. 65°C/6 min, 65°C – 95°C/15 min, 95°C – 40 min.	5	36	202	25°C – 65°C/20 min. 65°C/6 min, 65°C – 95°C/15 min, 95°C – 22 min.	30
4000	25°C – 65°C/20 min. 65°C/6 min, 65°C – 95°C/15 min, 95°C – 40 min.	5	32	180	25°C – 65°C/20 min. 65°C/6 min, 65°C – 95°C/15 min, 95°C – 22 min.	27.
5000	25°C – 65°C/20 min. 65°C/6 min, 65°C – 95°C/15 min, 95°C – 40 min.	5	28	157	25°C – 65°C/20 min. 65°C/6 min, 65°C – 95°C/15 min, 95°C – 22 min.	25

3. Determination of the refractive index and the thickness of the waveguide layer

In order to determine the refractive index of a step-index waveguide structure, based on the polymer SU8, the numerical method was applied, requiring the determination of the effective refractive indices for each observed mode. By means of mode spectroscopy a set of effective refractive indices was determined for the wavelength 633 nm, concerning the planar waveguides.

The synchronic angle was measured for the polymer waveguides obtained at rotational speeds of 2000, 3000 and 5000 rpm. Basing on the measured synchronic angle the effective refractive indices were calculated for all modes of each polarization. In the case of waveguides in which not more than two modes could be observed, the denotations 0 and 1 were applied successively, i.e. modes of the zero and first order. The effective refractive indices are connected with the refractive index resulting from the dispersive Eq. (1) [16].

$$\frac{2\pi}{\lambda} d(n_F^2 - N_m^2)^{1/2} = \Psi_m(n_F, N_m), \tag{1}$$

where λ – wavelength, d – thickness of the waveguide layer, n_F – refractive index of the waveguide layer, N_m – effective refractive index of the m-th mode.

The expansion of the characteristic function $\Psi_m(n_F, N_m)$, can be expressed by the relation (2) [16]:

$$\Psi_m(n_F, N_m) = m\pi + \phi_S(n_F, N_m) + \phi_C(n_F, N_m), \tag{2}$$

where m – number of the mode, ϕ_J – function ($J = S$ for the substrate, $J = C$ for the cover).

The functions $\phi_S(n_F, N_m)$ and $\phi_C(n_F, N_m)$ comply with (3).

$$\phi_J(n_F, N_m) = \arctan\left[\left(\frac{n_F}{n_J}\right)^{2\rho}\left(\frac{N_m^2 - n_J^2}{n_F^2 - N_m^2}\right)\right]^{1/2}, \tag{3}$$

where n_J – refractive index of the substrate at $J = S$ and the cover at $J = C$, ρ – identifier of the polarization ($\rho = 0$ for TE and $\rho = 1$ for TM).

Substituting the previously determined effective refractive indices for the mode of the zero order N_0 and first order N_1 into Eqs. (1), (2) and (3), and eliminating the index $2\pi d/\lambda$, we get the relation for the refractive index (4) [16].

$$n_F^2 = F(n_F^2), \tag{4}$$

where

$$F(n_F^2) = \frac{N_0^2 \mathbf{\Psi}_1^2 - N_1^2 \mathbf{\Psi}_0^2}{\mathbf{\Psi}_1^2 - \mathbf{\Psi}_0^2}. \tag{5}$$

Due to the form of Eq. (5), the refractive index can be calculated, applying the iterative method, presented in [16].

The considerations dealt with above are correct in the case of step-index waveguides. Having at one‘s disposal two values of the refractive index for each polarization, the refractive index of the waveguide layer can be determined for every arrangement of these values. The results of calculations of the values of the refractive index of waveguide layers have been gathered in Table 2. Any change of the thickness of the waveguide layer affects directly the number of waveguide modes propagating in it. Information about the thickness of the waveguide permit to assess the number of modes (at the selected wavelength) which propagate in the given structure and is of essential importance with respect to the arrangement of the system in which it is to be applied. The value of the refractive index obtained by means of spectroscopy permits in many cases to determine mathematically the thickness of the waveguide layer [16]. Another method is the measurement of the thickness by means of special devices.

Table 2
Results of measurements of the refractive index and thickness of waveguide layers SU8 at $\lambda = 633$ nm

Mode	Synchronic angle ϕ_m	N_{eff}	Numerically determined refractive index n	Numerically determined thickness [μm]
		Spin speed 2000 [rpm]		
TE_0	21.22	1.5781	**1.592**	**1.38**
TE_1	16.86	1.5420		
TM_0	21.14	1.5774		
TM_1	16.54	1.5393		
		Spin speed 3000 [rpm]		
TE_0	21.54	1.5806	**1.597**	**1.29**
TE_1	17.01	1.5433		
TM_0	21.37	1.5793		
TM_1	16.62	1.5399		
		Spin speed 5000 [rpm]		
TE_0	21.17	1.5777	**1.594**	**1.20**
TE_1	15.54	1.5305		
TM_0	21.08	1.5770		
TM_1	15.20	1.5275		

By solving Eq. (1), we obtain easily a formula, by means of which the thickness of the waveguide layer can be calculated (6) [16].

$$d = \frac{\Psi_m(n_F, N_m)}{k(n_F^2 - N_m^2)^{1/2}}. \tag{6}$$

For every combination of mode pairs the value of the thickness was determined basing on the previously calculated refractive index.

Table 2 contains the results of calculations of the thickness of the waveguide layer consisting of SU8. The calculations were based on data resulting from the analysis of mode spectra concerning the respective waveguide and on the previously calculated value of the refractive index. The obtained results conform with profilometrical measurements.

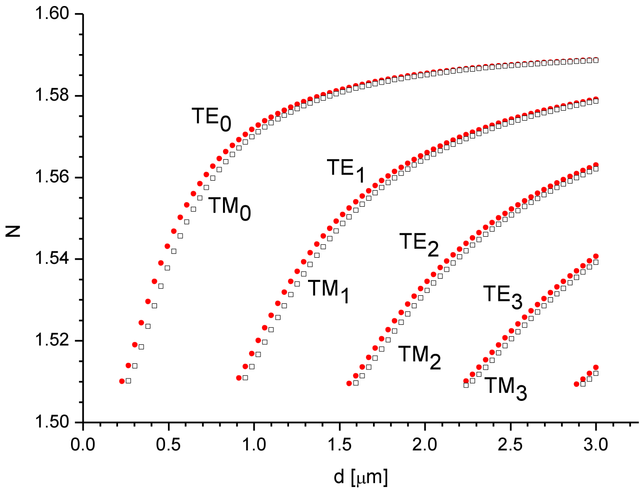

Fig. 1. Effective refractive indices as a function of the thickness d of the layer SU8

4. Differential interference in a single-mode waveguide

Knowing the refractive index of the layer SU8 and having the possibility of shaping the thickness of the layer by choosing the angular velocity of spinning, we can optimize the thickness of the refractive index of the cover. For a three-layer system with the following refractive indices: substrate $n_S = 1.509$, waveguide layer $n_F = 1.592$, cover $n_C = 1.330$, the effective refractive indices N were determined depending on the thickness of the layer concerning both polarizations TE and Tm for the wavelength $\lambda = 633$ nm (Fig. 1).

In the range of thicknesses of the waveguide layer from 0.25 μm to 0.86 μm the three-layer structure is a single-mode structure for the polarizations TE and TM. In the case of interferential system the most important parameter is the mode sensitivity $S\{n_C\}$, determining the changes of the effective refractive index ΔN due to changes of the refractive index of the cover Δn_C.

$$S\{n_C\} \cong \frac{\Delta N}{\Delta n_C}. \tag{7}$$

Knowing the effective refractive indices, the mode sensitivity can be determined.

The sensitivity $S\{n_C\}$ is determined by the formula [17]:

$$S\{n_C\} = \left(\frac{n_C}{N}\right) \times \left(\frac{n_F^2 - N^2}{n_F^2 - n_C^2}\right) \times \left(\frac{\Delta z_C}{d_{eff}}\right) \times \left(\frac{2N^2}{n_C^2} - 1\right)^{\rho}, \tag{8}$$

where

$$d_{eff} = d_F + \Delta z_C + \Delta z_S, \tag{9}$$

$$\Delta z_J^{(TE)} = \frac{\lambda}{2\pi} \frac{1}{\sqrt{N^2 - n_J^2}}, \tag{10}$$

$$\Delta z_J^{(TM)} = \frac{\lambda}{2\pi} \frac{1}{\sqrt{N^2 - n_J^2}} \times \left[\left(\frac{N}{n_F}\right)^2 + \left(\frac{N}{n_J}\right)^2 - 1\right]^{-1}. \tag{11}$$

The index ρ is equal to 0 for the TE type polarization ($\rho = 1$ for the TM type of polarization). The effective thickness d_{eff} (Eq. (9)) is marked as the total depth of light penetration. Equations (10) and (11) describe the depth of the evanescent field in the covering (substrate) layer for TE and TM polarization, respectively.

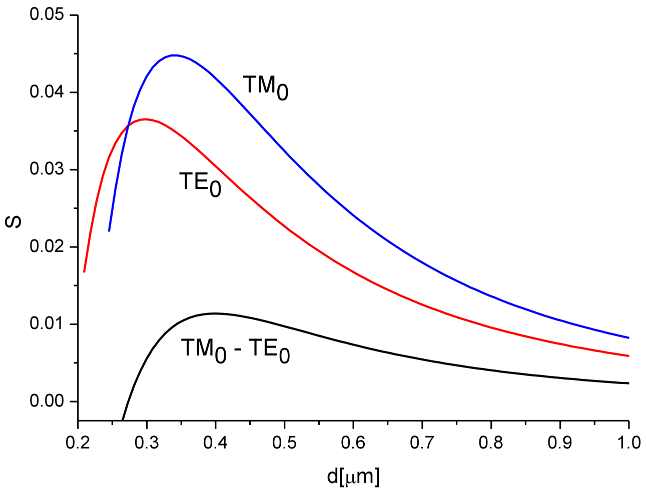

Fig. 2. Sensitivities as a function of the thickness of the waveguide layer concerning a single-mode waveguide

The differential interferometer is the planar waveguide based interferometic system, which can be realized most easily. In the waveguide two modes are excited, and a change of the refractive index of the covert involves changes of the effective refractive indices of the guided modes. The sensitivity of the differential interferometer $S_D\{n_C\}$ can be determined as differences of the mode sensitivity $S_i\{n_C\}$ and $S_j\{n_C\}$ of the guided modes:

$$S_D\{n_C\} = \frac{\Delta\left(N_i - N_j\right)}{\Delta n_c} = \frac{\Delta N_i}{\Delta n_c} - \frac{\Delta N_j}{\Delta n_c} = \\ = S_i\{n_C\} - S_j\{n_C\}. \tag{12}$$

In the range of thicknesses of the waveguide layer from 0.25 μm to 0.86 μm the three-layer structure is a single-mode structure for the polarizations TE and TM. In such case the sensitivity of the mode TM_0 for the single-mode waveguide $S_i\{n_C\}$ is determined, and $S_j\{n_C\}$ denotes the sensitivity of the mode TE_0. The calculated value of sensitivity have been presented in Fig. 2. In such a case the differential interferometer has the highest sensitivity equal to 0.011 for a thickness of the waveguide layer $d = 0.40$ μm.

5. Conclusions

The final aim of the presented investigations is elaboration of optical sensors of various physical values [18–23]. The investigations concerning the achievement of planar waveguides on a glass substrate indicate that the main problem is the adhesion of SU8 to the substrate. The adhesion can be improved by adequate rinsing and soaking previous to the deposition of the polymer. For the investigations waveguides were chosen which had been obtained at rotational speeds of 2000, 3000 and 5000 rpm, in which two modes of polarization TE and two with TM polarization were propagated. The aim of the investigations was to determine the effective refractive indices and to calculate the value of the refractive index and thickness of the waveguide layer. The obtained results prove the correctness of the assumptions, which had been made when the parameters of the technological process were being decided. The values of the refractive index concerning various thicknesses of the waveguides were similar.

The mode sensitivity was calculated as a function of the thickness in a single-mode structure. The thickness of thickness of that layer was determined in the case when the differential interferometer has the highest sensitivity to changes of the refracting index.

Acknowledgments. The work was sponsored by the State Committee for Scientific Research (NCBiR) within the grant N R01 034 06/2009.

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