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A suggestion of utilizing bimodal layers of the polymer SU8 for the purpose of monitoring the changes in the refractive index

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The paper presents the results of investigations concerning the measurements of the refractive index and the thickness of planar waveguide structures, obtained by photopolymerization of the polymer SU8. In the paper, the mode sensitivity has been calculated as a function of the thickness in a bimodal structure. The differential interference has been analyzed, concerning the modes of the same types TE_0–TE_1 and TM_0–TM_1. The thickness of the layer has been determined when the interferometer is most sensitive to the changes in the refractive index.

Keywords: 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 [1–10].

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 high thermal and chemical stability as well as good resistance to mechanical damages and 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, permits to obtain layers of thickness of 0.2 μm up to 2mm.

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 photoinitiator, *viz* Lewis acid, responsible for the initiation of cross-linking, in the course of which an epoxy ring is opened [11]. 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 techniques MEMS and MOEMS, being highly resistant and very sensitive photoresisting processes involving selective plasma digestion but also in photolithography. Because of its very good optical properties [12, 13] it is utilized in the production of optical sensors operating in the interferometer system [14].

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 [14]; 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 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 (relaxation 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 [14], after which the temperature of 65 °C was maintained for 10 minutes. The following step was the heating up from 65 °C to 95 °C with a surplus of 2 °C/min, with the latter temperature 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 250W) was adjusted individually for each thickness of the SU8 layer. 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 propylene glycol methyl ether acetate (PGMEA) [14]. After its development the structure was washed with isopropanol and dried at room temperature.

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 rpm, 3000 rpm 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 no 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 equation [15]:

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

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 [15]:

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

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:

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

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 the Eqs. (1), (2) and (3), and eliminating the index $2\pi d/\lambda$, we get the relation for the refractive index [15]:

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

where:

$$F\left(n_F^2\right) = \frac{N_0^2 \Psi_1^2 - N_1^2 \Psi_0^2}{\Psi_1^2 - \Psi_0^2} \tag{5}$$

Due to the form of the Eq. (5), the refractive index can be calculated, applying the iterative method presented in [15].

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 the Table. Any change in the thickness of the waveguide layer affects directly the number of waveguide modes propagating in it. Information about the thickness of the waveguide permits 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 [15]. Another method is the measurement of the thickness by means of special devices.

By solving Eq. (1), we obtain easily a formula, by means of which the thickness of the waveguide layer can be calculated [15]:

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

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

The Table contains the results of calculations of the thickness of the waveguide layer consisting of SU8. The calculations were based on data resulting from the analy-

T a b l e. Results of measurements of the refractive index and thickness of waveguide layers at $\lambda = 633$ nm.

Mode	N_{eff}	Numerically determined refractive index	Numerically determined thickness [μm]
		Spin speed 2000 [rpm]	
TE_0	1.5781	1.592	1.38
TE_1	1.5420		
TM_0	1.5774		
TM_1	1.5393		
		Spin speed 3000 [rpm]	
TE_0	1.5806	1.597	1.29
TE_1	1.5433		
TM_0	1.5793		
TM_1	1.5399		
		Spin speed 5000 [rpm]	
TE_0	1.5777	1.594	1.20
TE_1	1.5305		
TM_0	1.5770		
TM_1	1.5275		

sis of mode spectra concerning the respective waveguide and on the previously calculated value of the refractive index. The obtained results coincide with profilometrical measurements.

4. Bimodal waveguide applied as a refractometer

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 in order to achieve maximum sensitivity to changes in the refractive index of the cover [16].

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).

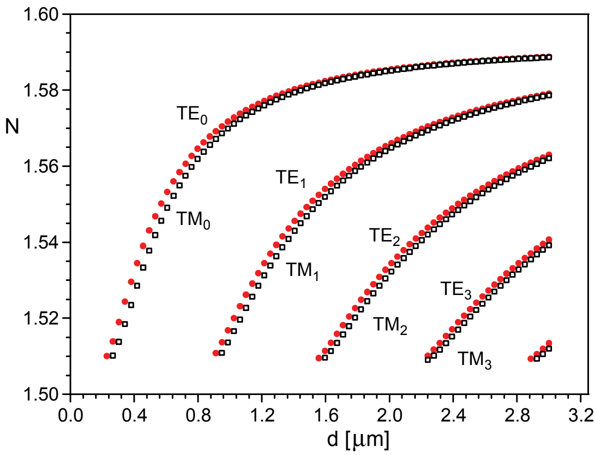

Fig. 1. Effective refractive indices as a function of the thickness d of the layer SU8.

In the case of an 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 in 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]:

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

where:

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

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

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

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 the penetration of light. Equations (10) and (11) describe the depth of the evanescent field in the covering (substrate) layer for TE and TM polarization, respectively. The calculated value of sensitivity has been presented in Fig. 2.

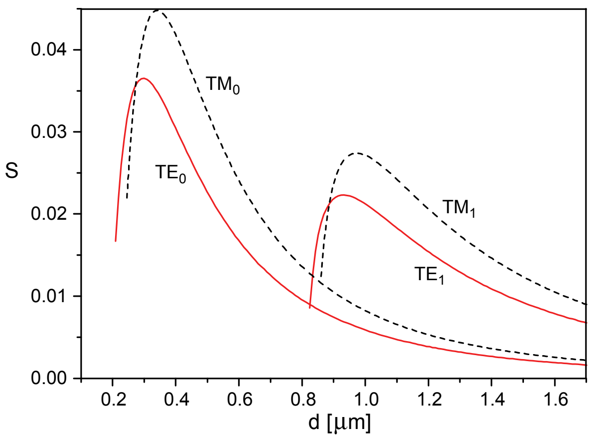

Fig. 2. Sensitivities as a function of the thickness of the waveguide layer.

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

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

In the range of thicknesses of the waveguide layer from 0.94 µm to 1.54 µm the three-layer structure is a bimodal structure for the polarizations TE and TM.

In such a structure the modes TE_0, TE_1, TM_0, TM_1 can propagate. In the course of recent years the application of various orders in the construction of a differential interferometer has been suggested [18–20]. Changes in the refractive index of the cover may be monitored by any arbitrary pair of modes. High sensitivity can be achieved when modes of the same types TE_0–TE_1 or TM_0–TM_1 are applied. Figure 3 presents the sensitivity of the modes TE_0 and TE_1, as well as the sensitivity of a differentia interferometer which operates basing on these modes. In the bimodal range of the waveguide thickness (0.94 μm to 1.54 μm) the sensitivity of the mode TE_0 is rather small, decreasing with the growth of the thickness, whereas the sensitivity of the mode TE_1 first increases and after reaching its maximum decreases with the growing thickness of the waveguide. The characteristics of the sensitivity of the differential interferometer are in this case similar to those of the sensitivity of the mode TE_1.

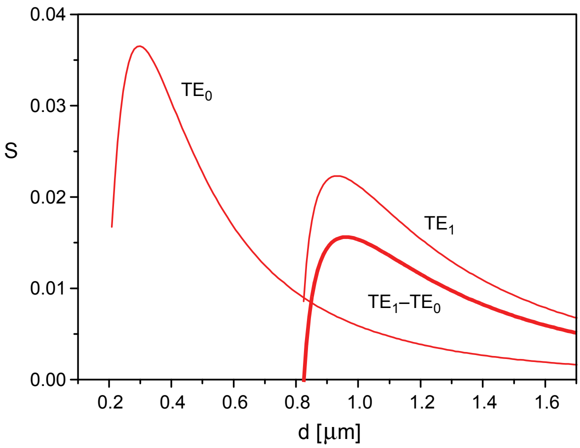

Fig. 3. Sensitivities as a function of the thickness of the waveguide layer at TE polarization.

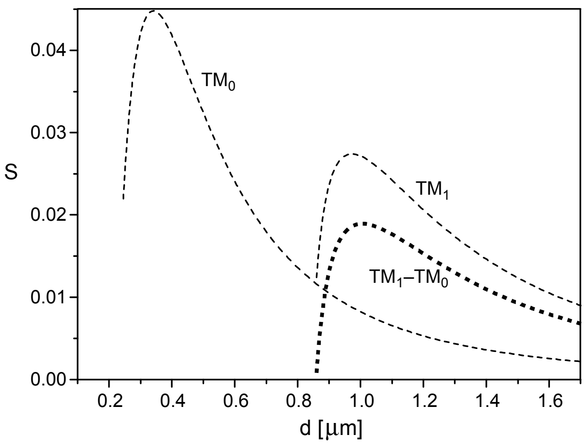

Fig. 4. Sensitivities as a function of the thickness of the waveguide layer at TM polarization.

The differential interferometer has the highest sensitivity equal to 0.016 at the thickness of the waveguide layer $d = 0.96$ µm.

Considering the interferences of the modes TM_0–TM_1, we see (Fig. 4) that the respective characteristics are similar. In such a case the differential interferometer achieves the highest sensitivity equal to 0.019 at a thickness of the waveguide layer $d = 1.01$ µm.

Figure 5 presents the sensitivities of the differential interferometer as a function of the thickness of the waveguide concerning modes of the same type (TE_0–TE_1, TM_0–TM_1) and modes of the same order (TE_0–TM_0, TE_1–TM_1). In the case of modes of the same type a higher sensitivity can be achieved than in the case of mode of the same order. The highest sensitivity is achieved by applying the interference of the modes TM_0–TM_1.

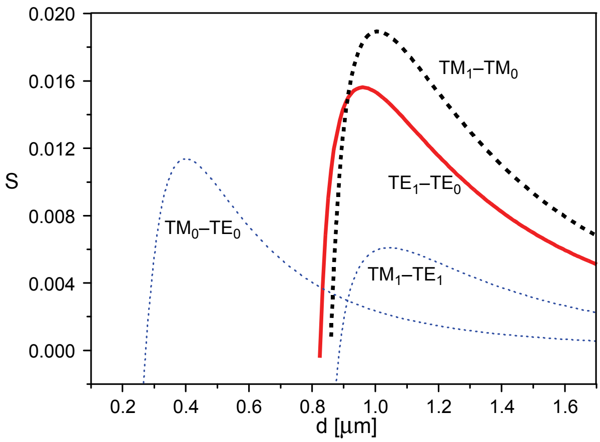

Fig. 5. Sensitivities as a function of the thickness of the waveguide layer concerning various pairs of modes.

The structure described above can be realized by constructing a waveguide, the segments of which are of different thicknesses. In the first single-mode only the basic mode propagates. In the second bimodal part the basic mode and the mode of the first order are excited providing that the required conditions are satisfied [20].

5. Conclusions

The final aim of the presented investigations was to develop optical sensors of various physical values [21–27]. The investigations concerned the achievement of planar waveguides on a glass substrate. For the investigations waveguides were chosen 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 mode sensitivity was calculated as a function of the thickness in a bimodal structure. By controlling the technological parameters in the process of the formation of layers of the polymer SU8, a precise thickness of the layer can be obtained (and thus also the number of propagating modes). The application of modes of the same types (TE_0–TE_1 or TM_0–TM_1) permits to achieve a higher sensitivity than in the case of modes of the same orders (TE_0–TM_0, TE_1–TM_1). The highest sensitivity is obtained by applying the interference of the modes TM_0–TM_1.

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