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Planar Optical Waveguide Sensor Structures with Grating Couplers

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The paper presents optical planar waveguide sensor structures with grating couplers of groove density $\chi = 2400$ g/mm. The waveguide films were obtained using sol-gel method, in which the grating couplers were fabricated by the embossing method. The results of theoretical analysis as well as the results of experimental research have been presented.

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1. Introduction

Planar evanescent wave chemical and biochemical sensors are multi-layer systems consisting of a waveguide layer deposited on an optical substrate and coated by a sensor layer. The evanescent field of the wave propagating in the waveguide layer penetrates the sensitive film. In biochemical sensors, the role of a sensitive film can be taken up by the liquid covering the waveguide. The change of refractive index of the cover or the change of sensitive film thickness results in the change of effective indexes of the guided modes [1]. These changes can be measured in interferometer systems or with the use of grating couplers.

The paper presents planar waveguide sensor structures with input grating couplers to be applied in evanescent field spectroscopy. The results of theoretical investigations and of experimental research have been presented. Detection thresholds involving the changes of refractive index and the changes of sensor layer thickness have been provided.

2. Sensor structure

A grating coupler is a system of periodic disturbance in a planar waveguide (Fig. 1). Grating couplers enable a very effective introduction of light into planar waveguides [2]. The coupling condition is defined by the following dependence:

$$\sin\theta_m = n_p^{-1}\left(N - m\frac{\lambda}{\Lambda}\right), \qquad (1)$$

where m is a diffractive order, N is an effective refractive index of the excited mode, λ stands for wavelength and n_p is the refractive index of the environment where the θ_m angle is measured. The change of the refractive index of the cover n_c or the change of sensitive film thickness w results in the change of effective refractive indexes N. As it follows from (1) also the coupling angles θ undergo changes. Small changes of the refractive index of the cover Δn_c and of sensitive film thickness Δw correspond to the change of effective refractive index

$$\Delta N = \left(\frac{\partial N}{\partial n_c}\right)\Delta n_c + \left(\frac{\partial N}{\partial w}\right)\Delta w, \qquad (2)$$

where $(\partial N/\partial n_c)$ and $(\partial N/\partial w)$ stand, respectively, for homogeneous sensitivity and surface sensitivity. Their values depend on the parameters of the waveguide layer, the substrate and the cover. The change of the effective refractive index ΔN denotes the change of coupling angle

$$\Delta\theta_m = (n_p\cos\theta_m)^{-1}\,\Delta N. \qquad (3)$$

The above equation is a basis for grating coupler sensors.

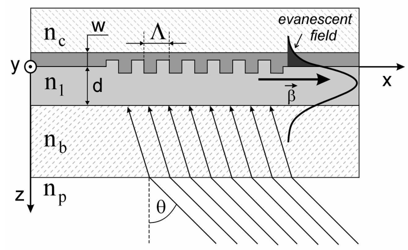

Fig. 1. Planar sensor structure.

Planar slab waveguides of high refractive index ($n \approx 1.8$) were produced in sol-gel technology [3, 4]. The layers SiO_2:TiO_2 were coated on BK7 glass substrate using dip-coating method. The couplers of the groove density $\chi = 2400$ g/mm were produced with the application of commercially available holographic master gratings. After the sol film had been deposited on the substrate, a relief of master grating was embossed in it. Then the structures were heated for 1 h at the temperature of 500 °C.

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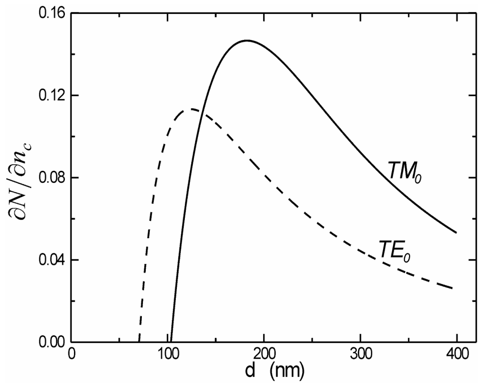

Fig. 2. Homogenous sensitivities versus waveguide film thickness. $n_c = 1.330$.

Figure 2 presents the calculated dependences of the homogeneous sensitivity on the waveguide thickness d of the refractive index $n_1 = 1.800$, on BK7 glass substrate ($n_b = 1.5137$). For the mode TE_0 the homogeneous sensitivity reaches the maximum value of $(\partial N/\partial n_c)_{max} = 0.113$ for the waveguide layer thickness $d = 124$ nm. For the mode TM_0 the homogeneous sensitivity reaches the maximum value of $(\partial N/\partial n_c)_{max} = 0.147$ for $d = 182$ nm. The influence of the parameters of the planar sensor structure on the obtained sensitivities was extensively discussed in Ref. [5].

3. Experimental results

The measurement setup applied in the research was described in works [5, 6]. The produced sensor structures were investigated in view of their application for the determination of refractive index. The structures within the area of grating coupler were coated with liquid of the known refractive index, and coupling characteristics were recorded. The exemplary model spectra recorded for the selected refractive indexes of the cover are presented in Fig. 3. For the case of the investigated structure ($\chi = 2400$ g/mm) the coupling angles are negative (Fig. 1). Negative values of the coupling angle θ correspond to the signals recorded from the left-hand edge of the structure, and the positive values correspond to the signals recorded from the right-hand edge of the structure. We can observe sharp coupling peaks which change their position with the change of refractive index of the cover n_c. The rise of refractive index of the cover results in the rise of effective refractive indexes N, and, in consequence, in the rise of the value of coupling angles θ (Eq. (1)). The half width values at half maximum of the coupling peaks for the produced structures were within the range from 0.023° to 0.050°. The coupling peaks are symmetrical to the normal ($\theta = 0°$). Therefore, by recording the coupling peaks with the structure being excited from the left- and right-hand side of the structure with respect to the normal (Fig. 1) the coupling angle is equal to the half of their angular distance. Such a procedure eliminates the process of normal determination error. The coupling peaks were approximated with Gauss function, which enabled the determination of coupling angles with the resolution of $\Delta\theta_{min} = 10^{-6}$ rad.

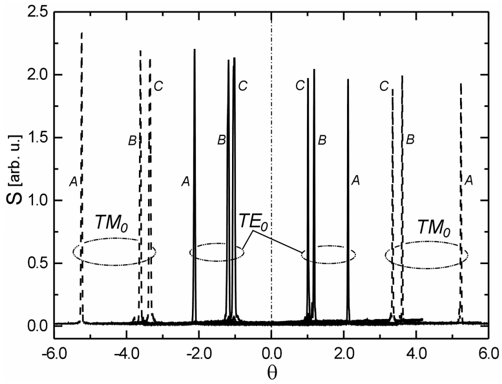

Fig. 3. Incoupling characteristics of the sensor structure for selected cover refractive indexes. $n_1 = 1.801$, $d = 184$ nm, $A - n_c = 1.0003$, $B - n_c = 1.3335$, $C - n_c = 1.3638$.

The dependence of coupling angles on the refractive index of the cover for modes TE_0 and TM_0 are presented in Fig. 4. Squares and triangles were used to mark experimental points and solid lines were used to define theoretical dependences. Using (1) we can determine the dependence of effective indexes on the refractive index of the cover. The minimum changes of effective indexes that can be recorded in the applied measurement system are $\Delta N_{min} = 10^{-6}$. It follows from Eq. (2) and from the results of theoretical analysis (Fig. 2) that the minimal changes of refractive index of the cover, which can be recorded with the application of the presented structures are $(\Delta n_c)_{min} \approx 7 \times 10^{-6}$.

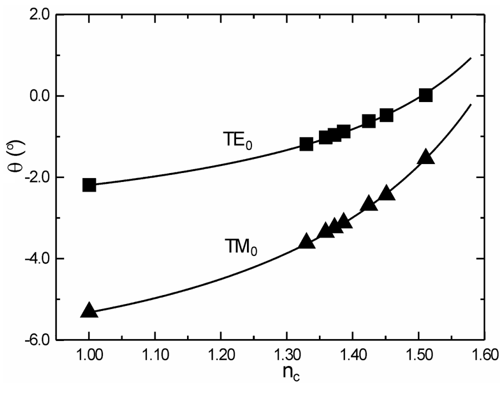

Fig. 4. Influence of cover refractive index on the coupling angles.

Considering the changes of sensitive film thickness (assuming that sensitive film thickness $w = 1$ nm, refractive index of the sensitive film $n_w = 1.50$, refractive index of the cover $n_c = 1.33$) we can conclude that the minimal changes of sensitive film thickness, which can be detected with the use of the presented structures are $\Delta w_{\min} = 3.1 \times 10^{-3}$ nm.

4. Summary

The paper presents planar waveguide sensor structures with grating couplers for the application in evanescent field spectroscopy. The estimated detection thresholds are respectively 10^{-6} for the changes of effective indexes, 7×10^{6} for the changes of refractive index of the cover and 3.1×10^{-3} nm for the changes of sensitive film thickness. The presented structures are suitable for chemical and biochemical measurements, including the run of immunoreaction.

Acknowledgments

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