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Numerical characteristics of the polarimetric interferometer made by K^+-Na^+ ion exchange

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The paper presents numerical optimizing investigations of planar polarimetric interferometer made by K^+-Na^+ ion exchange in glass for sensor applications. Two cases are considered – phase modulation of guided light waves caused by refractive index changes of the waveguide cover for applications of the polarimetric interferometer as refractometer or chemical sensor, and phase changes induced by nanometer movements of a dielectric layer separated from the waveguide by an air gap of the width below wavelength of light for using the polarimetric interferometer as an acoustical transducer and pressure or displacement sensor.

1. Introduction

In 1991, LUKOS and PLISKA [1] presented the conception of integrated optical polarimetric (or difference) interferometer (PI) fabricated by dip-coating (solgel process) on oxidized silicon wafers as substrate. The interferometer is characterized by a simple construction based on the intermode interference between orthogonal modes guided in the planar waveguide and great possibilities of practical applications as modulators, switches, acoustical sensors [2] and as refractometers and chemical sensors [3].

For the PI fabrication, we proposed in [4] a technologically much simpler method of ion exchange in glass which is particularly useful for the production of gradient index profiles. In the single-mode planar optical waveguides, two modes TE and TM propagate. In general, their properties are defined by different dispersion equations and, hence, external propagation conditions will have different influence on both modes. If a sensor layer is placed over the strip optical waveguide, then the guided light penetrates the layer (*evanescent field*) and a change of the effective refractive indices of the guided modes is observed. Therefore, there will be a phase shift, occurring between the guided modes at the output of the optical waveguide, which is a function of the refractive index of the layer.

Modal properties of the gradient-index waveguides which decide about the working characteristics of the PI can be easily controlled by the technological process conditions – time of diffusion, window opening and time of heating of the waveguides fabricated in initial diffusion process and by light propagation conditions. Two cases of changes of external light propagation conditions are considered

– changes induced by the moving dielectric layer, separated from the waveguide by an air gap of the width below wavelength λ for the PI application as an acoustical transducer and changes of the refractive index of the cover for PI applications as a refractometer and chemical sensors. The aim of this work is to determine the influence of the technological process parameters and boundary condition variations on modal properties of waveguides obtained and optical characteristics of the polarimetric interferometer.

2. Gradient-index polarimetric interferometer

The basic element of the examined planar polarimetric interferometer is the monomode gradient-index lightguide, planar or strip made by $K^{+}-Na^{+}$ ion exchange. Material parameters of the technological process, *i.e.*, self-diffusion coefficient of K^{+} ions D, the mobility ratio of the ions K^{+} and Na^{+}, and the maximum of the refractive index change are determined by measurements of respective planar index profiles using IWKB method. Based on the above, the nonlinear diffusion equation [5] is solved by an explicit finite difference scheme. Surface and heating profiles are modelled by using appropriate initial and boundary conditions.

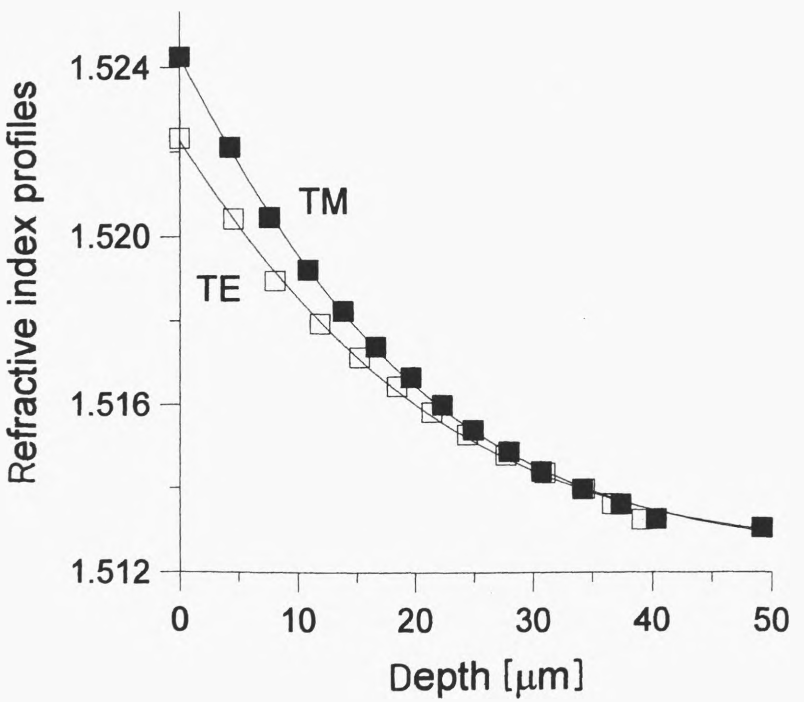

Fig. 1. Distribution profiles of the refractive index for the polarization TE and TM for the waveguide produced in the diffusion process at temperature 400 °C and time 165 h

Figure 1 presents distribution profiles of the refractive index for the polarization TE and TM, obtained in the diffusion process of potassium ions to the glass BK-7 at temperature 400 °C and time 165 h. The self-diffusion coefficient determined equals 2.18 $\mu m^2/h$ for both profiles, whereas the distribution maxima on the surface are $\Delta n_{TE} = 0.0095$ and $\Delta n_{TM} = 0.0117$, respectively. The observed differences in the distribution of the refractive index for both orthogonal polarizations result from the anisotropy of strains taking place during the technological process, and are of significant importance for performance characteristics of the difference interferometer [4].

Modal properties of numerically modeled waveguide structures were determined by an effective index method [6]. The variations of the light propagation conditions induce changes in the difference of the propagation constants $\Delta\beta = \beta_{TE} - \beta_{TM}$ of the TE and TM modes proportional to the magnitude of the disturbance and determine their phase difference at the end of the waveguide

$$\Delta\Phi = L \cdot \Delta\beta \tag{1}$$

where L is the length of the interaction area. Putting on the waveguide output, a properly oriented polarizer (at $\pm 45°$ to the waveguide plane) modulated by the phase changes, optical intensity P can be measured on the photodetector

$$P = P_0/2(1+\cos(\Delta\Phi)) \tag{2}$$

where P_0 is the intensity guided in both orthogonal modes.

3. Polarimetric interferometer as an acoustical transducer

The PI scheme in the configuration of an acoustical transducer is shown in Fig. 2. We can distinguish here the monomode gradient index strip waveguide (W) on a glass substrate. A dielectric layer (DL) of the refractive index $n_D \leqslant n_S + \Delta n$ positioned at the distance below wavelength of light is the active mechanical

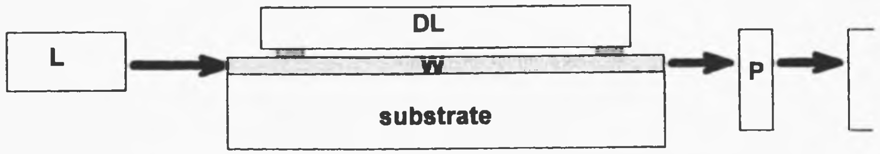

Fig. 2. Scheme of an acoustical transducer configuration. L – laser, W – gradient index waveguide, DL – dielectric layer, P – polarizer, D – photodetector

element of the transducer. The waveguide is separated from the dielectric layer by a thin air gap. The movement of the layer DL induced, for example, by acoustical pressure changes determines in a different way the penetration depth of the evanescent fields of TE and TM modes and the boundary condition for their propagation. The propagation constants difference $\Delta\beta$ is therefore the function of the air gap thickness d.

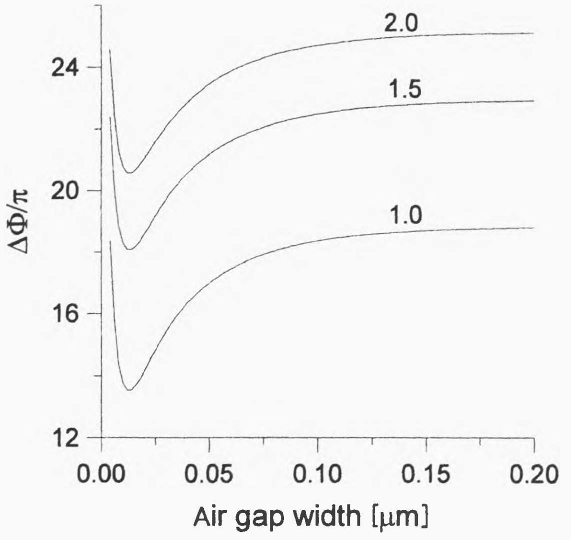

Fig. 3. Phase difference (in π units) for the interaction length $L = 1$ cm ($\lambda = 632.8$ nm) as a function of the gap width for the different time of diffusion $t_D = 1$ h, 1.5 h, 2 h, $n_D = 1.5125$

Figure 3 presents the dependence of the phase shift $\Delta\Phi$ (in π units) at the end of the interferometer on the air gap thickness for the interaction length $L = 1$ cm ($\lambda = 632.8$ nm), for the gradient index waveguides fabricated by the thermal diffusion process in time $t_D =$ 1 h, 1.5 h, 2 h through the mask openings $w = 4$ μm. For the shallow waveguides ($t_D = 1$ h) the influence of external boundary condition changes on the light propagation is stronger and the increase of the propagation constant difference for TE, TM modes with the decrease of the time of diffusion is observed. The sensitivity S_A of the displacement transducer defined as $\delta(\Delta\Phi)/\delta d$, calculated at the working point $d = 0.05$ μm. changes monolitically from 50 μm^{-1} for $t_D = 2$ h to 55 μm^{-1} for $t_D = 1$ h.

Similar results obtained for the waveguides fabricated by the thermal diffusion process in time $t_D = 2$ h through the mask openings w of the width $w = 1$, 1.2, 1.4, 2 (in $\sqrt{D \cdot t_D}$ units) are shown in Fig. 4. The spreading of the window width results in an increase of asymmetry degree of the waveguide and enlarges the propagation constant difference for TE, TM modes. The sensitivity S_A of the displacement calculated at the working point $d = 0.05$ μm, changes monolitically from 38 μm^{-1} for $w = 1$ to 51.6 μm^{-1} for $w = 2$.

Figure 5 presents optical characteristics of the PI for the waveguide produced in a two-stage process consisting of initial diffusion and heating. We considered the initial diffusion process ($t_D = 1$ h) through the mask of the width $w = \sqrt{D \cdot t_D}$ and heating in time $t_h = 0.5$, 1, 2 h. The increase of the time of heating improves the strip waveguide symmetry and reduces dynamics of working characteristics of the PI as an acoustical sensor. The sensitivities of transducers decrease with the time of heating, and at the working point $d = 0.05$ μm they are equal to 6.1, 12.2 and 18.2 μm^{-1}, respectively.

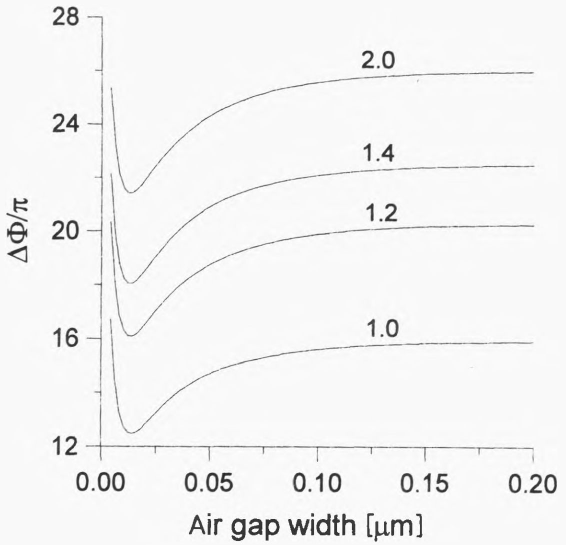

Fig. 4. Phase difference (in π units) for the interaction length $L = 1$ cm ($\lambda = 632.8$ nm) as a function of the gap width for the different mask opening $w = 1$, 1.2, 1.4, $2\sqrt{D \cdot t_D}$, $n_D = 1.5125$

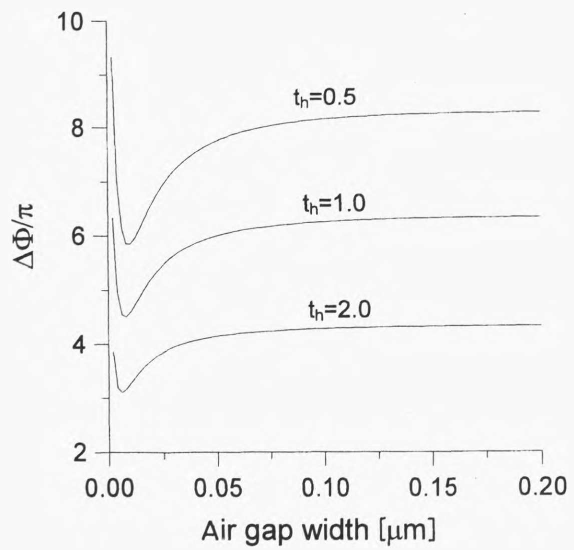

Fig. 5. Phase difference (in π units) for the interaction length $L = 1$ cm ($\lambda = 632.8$ nm) as a function of the gap width for the different time of heating $t_h = 0.5$, 1, 2 h, $n_D = 1.5125$

In Figure 6, the influence of the external dielectric layer DL on the transducer characteristic is presented. The analysis concerns gradient waveguide made for the process parameters $t_D = 2$ h, $w = 2\sqrt{D \cdot t_D}$ and for the refractive indices of the layer $n_D = 1.5125$, 1.51, 1.49. The increase of the refractive index influences the depth

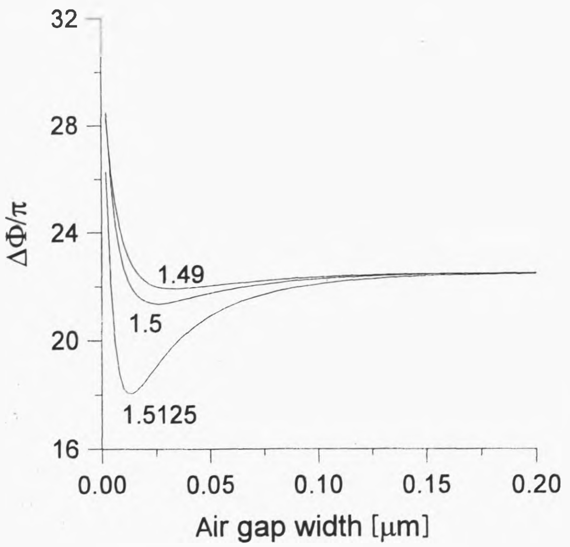

Fig. 6. Dependence of the phase difference (in π units) for the interaction length $L = 1$ cm ($\lambda = 632.8$ nm) on the gap width for the different refractive indices of the external dielectric layer

penetration of the evanescent field of both modes increasing working sensitivity of the transducer. The sensitivities obtained at $d = 0.05$ μm are equal to (50.1, 16.7, 9.1) μm^{-1}, respectively.

4. Polarimetric interferometer as a refractometer

For the PI applications as a refractometer, the difference propagation constants variations are realized by changes of the refractive index n_c of the cover of the gradient index strip waveguide. Figures 7–10 present numerically calculated working characteristics of the PI as a refractometer as a function of the time of diffusion (for the mask opening width $w = 4$ μm), as a function of the mask opening width (for the waveguides obtained in the time of diffusion process $t_D = 2$ h), as a function of the time of heating (for the technological process parameters $t_D = 1$ h, $w = \sqrt{D \cdot t_D}$) and as a function of the thickness of the cover. In every case considered, the increase of the refractive index of the cover increases the phase difference $\Delta\Phi$ for both orthogonal modes. The dynamics of the working characteristics increases near the cut-off point of the waveguide. The working sensitivity S_R of the refractometer defined as $\delta(\Delta\Phi)/\delta n_c$, calculated for example for the interferometer obtained at $t_D = 2$ h and $w = 2\sqrt{D \cdot t_D}$, grows monolitically in the whole refractive index variation range from the value $S_R = 12.2$ at $n_c = 1$ to the value 158.5 near the cut-off point of the waveguide. Choosing as a working point the value $n_c = 1.5$, the sensitivities S_R (124, 134, 155), (119.7, 134.2, 147.6, 158.5) and (27, 52.2, 87.5) are obtained, respectively, for the characteristics presented in Figs. 7–9.

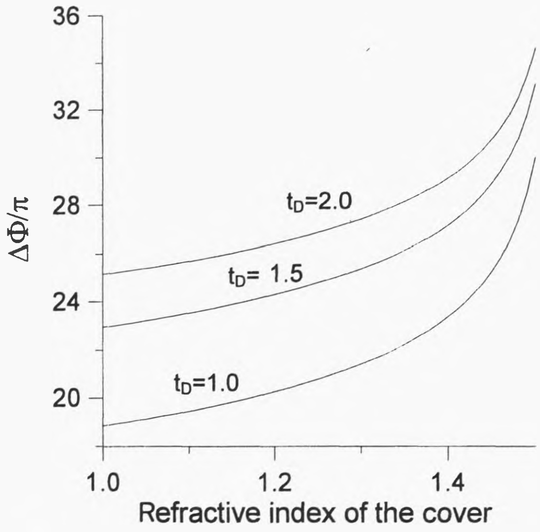

Fig. 7. Phase difference (in π units) for the interaction length $L = 1$ cm ($\lambda = 632.8$ nm) as a function of the refractive index of the cover for the different time of diffusion $t_D =$ 1 h, 1.5 h, 2 h, $n_D = 1.5125$

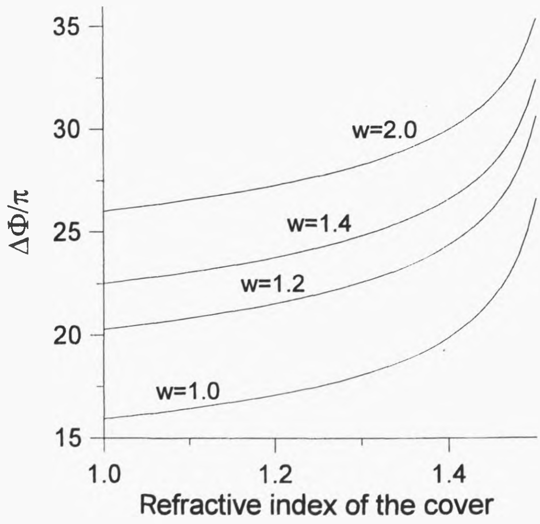

Fig. 8. Phase difference (in π units) for the interaction length $L = 1$ cm ($\lambda = 632.8$ nm) as a function of the refractive index of the cover for the different mask opening $w = 1, 1.2, 1.4, 2\sqrt{D \cdot t_D}$, $n_D = 1.5125$

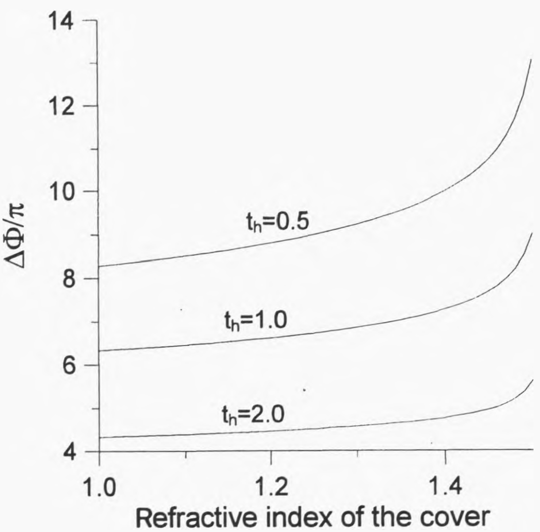

Fig. 9. Phase difference (in π units) for the interaction length $L = 1$ cm ($\lambda = 632.8$ nm) as a function of the refractive index of the cover for the different time of heating $t_h = 0.5, 1, 2$ h, $n_D = 1.5125$

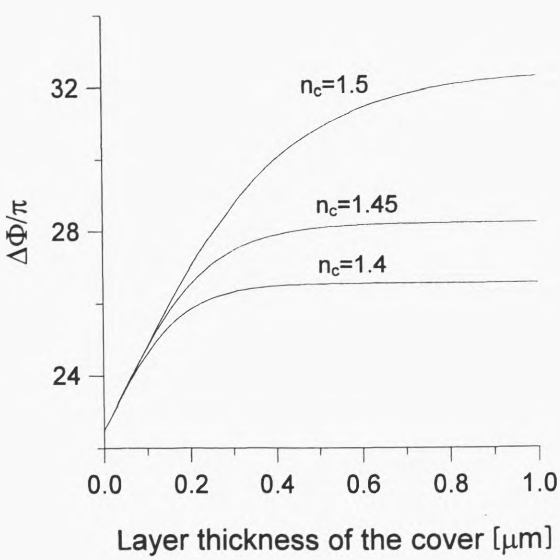

Fig. 10. Dependence of the phase difference (in π units) for the interaction length $L = 1$ cm ($\lambda = 632.8$ nm) on the refractive index of the cover for the different thickness of the dielectric layer

5. Conclusions

In the paper, the possibilities of applying K^+-Na^+ ion exchange technology for production of the planar PI in the configuration of an acoustical transducer and refractometer are examined.

The working characteristics of the acoustical transducer show that the position variations of moving dielectric layer of a few nanometers induce measurable phase changes at the output of the device. For a monomode waveguide ($\lambda = 632.8$ nm) produced for the process parameters $t_D = 2$ h, $w = \sqrt{D \cdot t_D}$ and interaction length $L = 2$ cm, for example, a phase shift $\Delta\Phi \sim \pi$ is achieved by a gap thickness variations ~ 10 nm at the working point $d = 0.05$ μm which is sufficient for technical applications.

Similar results are obtained for the working characteristics of the PI as a refractometer. The sensitivity $S_R = 158.5$, calculated near the point $n_c = 1.5$, for the waveguides obtained for the process parameters $t_D = 2$ h, $w = 2\sqrt{D \cdot t_D}$ ($L = 1$ cm) makes it possible to achieve phase changes $\Delta\Phi \sim \pi$ at the refractive index variations $\Delta n_c \sim 0.006$. The refractometer presented can be applied in the measurement of other physical quantities like liquid density or temperature. With an appropriate cover it can be also used as a sensor of pH reaction or gas concentration.

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