Planar gradient tapered waveguide in glass

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The paper presents fabrication technology of planar gradient tapered waveguide structures using the ion exchange technique in glass. Theoretical predictions of model properties have been compared with experimental results. Application possibilities of these waveguides in sensor related techniques have been pointed out.

Keywords: ion exchange, planar waveguides, waveguide sensors.

1. Introduction

Waveguide structures are often applied in sensor related engineering where they are sometimes used as alternative solutions for electronic sensors. In view of different character of their fabrication technology (distribution of refractive index), they can be basically divided into two groups: fibre waveguides and planar waveguides fabricated “in” or “on” glass substrates, either crystalline or semiconductor ones. Since the phenomenon of light propagation in waveguide structure allows as such for influence of the structure’s surroundings (refractive index, absorption), planar waveguides, as opposed to fibre waveguides, are characterised by higher “susceptibility” to the outside influence resulting from the technology of their fabrication. The group of planar waveguides is very amply represented (due to relatively simple and cheap technology) by waveguides produced on glass substrates with the use of ion exchange technique. In the least complicated version of ion exchange technique, liquid sources of admixture ions are used (melted nitrates) as well as glass substrates containing a considerable amount of the ions of alkali metals (modifiers) having relatively low activation energy. Waveguides fabricated with that technique are characterised by gradient distribution of refractive index spreading from the surface of glass substrate down till the depth of several to around a dozen or to around a few dozen micrometers. The depth (thickness) of the obtained structure is conditioned by the following factors: time of exchange process (diffusion) and temperature. The thickness of waveguide layer determines the character of its transmission properties with respect to the number of guided waveguide modes. Irrespective of the distribution character of refractive index, stemming from particular production technology, the number of modes which can propagate in the waveguide (with the determined wavelength) is an increasing function of its thickness.

The above relation can be used for the construction of sensor based on waveguides of variable thickness [1]. Such waveguides – in the following part referred to as tapered waveguides – are characterised by continuous change of propagation conditions of the guided modes. Structures of that type can be produced in different technological processes. They can have invariable refractive index and continuously changing thickness (e.g., Ta$_2$O$_5$, TiO$_2$ layers on quartz or glass substrates coated by cathode evaporation [2]. Variable thickness of the waveguide layer in ion exchange technique is obtained by thermal diffusion in the substrate gradually immersed in liquid admixture source [3], application of non-homogeneous electric field in the electro-diffusion process [4], application of partially permeable masking layer of variable thickness [5] and diffusion from the source in the form of a thin layer of changing thickness coated on glass substrate. In the tapered waveguide, two phenomena connected with the propagation of the selected waveguide mode can be observed: change of propagation direction resulting from the Snellius law for planar optics and cut-off of the mode connected with thickness change of the layer. In the second case, the energy carried by the waveguide mode is passing from the substrate, propagating at small angle to the surface of the waveguide [6].

2. Fabrication technology of tapered waveguides

The present investigation studies involve waveguide structures produced with the use of ion exchange technique Ag$^+\leftrightarrow$Na$^+$ in sodium-calcium glass, with the application of melted AgNO$_3$ as the source of admixture ions. Variable thickness of waveguide layer was obtained by gradual (with constant rate) immersion of substrate in liquid nitrate (Fig. 1). Single-mode structures were produced, with wavelength range 500–700 nm. The obtained paths of the tapered area were L = 50 mm. In the place where the diffusion process was lasting the longest, the waveguide was the thickest (the value of the thickness depends on the duration.
of the process) — in the following part this place will be referred to as the waveguide’s beginning. For theoretical modelling of ion exchange process in glass, the description of the phenomenon was used which allows for the dependence of diffusion constants $D_A$ and $D_B$ of the exchanged ions on their normalised concentrations as given in Ref. 7

$$
\begin{align*}
    D_A(u) &= D_{0A} \exp(Au) \\
    D_B(w) &= D_{0B} \exp(Bw)
\end{align*}
$$

(1)

where $u$, $w$ stand for normalised concentrations of admixture ions (Ag⁺) and glass (Na⁺), respectively, satisfying the condition $u + w = 1$. The equation describing time-space changes of normalised concentration of admixture ions introduced to glass assumes the following form [7]

$$
\frac{\partial u}{\partial t} = \frac{D_A}{1 - \alpha u} \left[ \Delta u + \frac{\alpha}{1 - \alpha u} (\nabla u)^2 \right] + \\
\frac{1 - u}{(1 - \alpha u)^2} \nabla u \cdot \nabla D_A + \frac{u(1 - \alpha)^2}{(1 - \alpha u)^2} \nabla u \cdot \nabla D_B
$$

(2)

In the above equation, $\alpha = 1 - D_A/D_B$. The values of the parameters $D_{0A}$, $D_{0B}$, $A$, and $B$ were determined by matching the solution of Eq. (2), describing the ion exchange kinetics for 1-dimensional case, with the determined (IWKB procedure) refractive profile of planar waveguide. The description of diffusion process with gradual immersion of substrate with the use of Eq. (2) requires respective boundary conditions to be provided.

Knowing the parameters characterising the kinetics of ion exchange and the dispersion of substrate glass $N_f(\lambda)$ as well as the value of the maximum change of refractive index on glass surface $\Delta n(\lambda)$, we can determine the time of diffusion as a result of which planar waveguide (of constant thickness) is produced, and which enables the propagation of only base modes $\text{TE}_0$ and $\text{TM}_0$ in the visible spectrum range. For sodium-calcium glass used for substrate purposes, the diffusion time is about 4 minutes at process temperature $T = 266^\circ\text{C}$. Assuming the total range of substrate immersion $L = 54.5$ mm, and basing on Eq. (2) with respective boundary conditions Eq. (3), theoretical distribution of normalised concentration of admixture $u(x,y)$ in the tapered waveguide was calculated. From that distribution, we can obtain refractive profiles of the waveguide for given wavelengths according to the following relation

$$
n(x,z,\lambda) = N_f(\lambda) + \Delta n(\lambda)u(x,z)
$$

(4)

Refractive profile for the cross-section $n(x,z = z_c)$ is in the discussed case a slow variable function of the value $z_c$.

In such a situation, the local value of effective refractive index of the mode can be determined as for the planar waveguide of the refractive profile $n(x,z = z_c)$ from the modal equation [8].

$$
k_0 \int_0^{x_c} \frac{n^2(x) - N_m^2}{n_c^2} dx = \pi (m + 0.25) + \\
+ \arctg \left( \frac{n_m}{n_c} \right) \left( \frac{N_m - N_c^2}{n_m^2 - N_m^2} \right)
$$

(5)

where $k_0 = 2\pi/\lambda$, $x_c$ is the turning point of $m$-th mode, $n_m$ is the refractive index on waveguide’s surface, $n_c$ is the refractive index of waveguide’s cover, $\gamma = 0$ for polarisation TE or $\gamma = 2$ for polarisation TM. Figure 2 presents the values of effective refractive indexes of modes $\text{TE}_0$ and $\text{TM}_0$ ($\lambda = 677$ nm) measured with a prism coupler, in a few selected waveguide cross-sections, as compared with the runs calculated with the use of modal equation for the profile, Eq. (4).

3. Light propagation in gradient tapered waveguide

As it has already been mentioned in the introduction, there are two phenomena taking place in tapered waveguides connected with the propagation of waveguide modes. The first one involves the dependence of propagation direction of the $m$-th mode on the changes of its effective refractive index $N_m$, which results from the Snellius law for planar...
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Fig. 2. Changes of effective refractive indexes of modes TE\textsubscript{0} and TM\textsubscript{0} along tapered waveguide for \( \lambda = 677 \) nm.

optics: \( N_m \sin \phi_m = \text{const} \), where \( \phi_m \) stands for the angle between the propagation direction of the mode and changes gradient \( N_m \) (which has been effected by the changes of waveguide's thickness). Therefore, using geometrical terms, we can determine the trajectory of the ray representing a given mode. Using the differences involving the changes of modes' trajectories for different wavelengths, resulting from chromatic dispersion of the waveguide, we can determine spatial separation of the modes. Due to small values of changes \( n \) obtained in the ion exchange process (\( \Delta n \approx 0.09 \) for the exchange \( \text{Ag}^+\leftrightarrow\text{Na}^+ \)) and small dispersion \( \Delta n(\lambda) \), the value of spatial separation is low (fractions of mm) for propagation path of around several dozen mm. The other phenomenon connected with wave propagation in the structure of a tapered waveguide is referred to as mode's cut-off. Waveguide mode of the wavelength is propagating along the direction of the changes of waveguide's thickness (axis \( z \)), and after it has arrived at the place \( z_0 \), at which there are no conditions for its further propagation, it is radiated off to the substrate (Fig. 3). Defining the cut-off value of mode \( z_0 \) (Fig. 3) as the distance from the beginning of the waveguide to the point of its cut-off, and by calculating from Eq. (5) the value of effective refractive index as the function \( N(z) \), we can determine the value of cut-off value for the investigated range of wavelengths. With respect to the produced waveguide structure, the results of carried out numerical calculations, allowing for both polarisation types of modes, with refractive index of waveguide's cover \( n_c = 1 \) (air) are presented in Fig. 4. As it can be seen from the diagrams, the change range of cut-off values of the waves within spectral range 510–690 nm has the value of around several mm. It can be also seen that the cut-off values of the modes of wave propagating as the mode TE\textsubscript{0} or the mode TM\textsubscript{0} are different. Cut-off value for the mode TM\textsubscript{0} is smaller than the cut-off value for the mode TE\textsubscript{0} for a definite value of \( \lambda \). Figure 5 presents the measurement method of spectral characteristics of light propagating in the waveguide after the cut-off of wavelength \( \lambda_0 \), at the distance \( z_0 \) from the waveguide's beginning. A halogen illuminator was used as the source of white light. Non-polarised light beam was introduced to the waveguide by means of a prism coupler PR. The same prism was used to introduce waves propagating in the waveguide's area located \( z_0 \) away from its beginning. Spec-

Fig. 3. Defining the cut-off value of the mode \( (\lambda_1 > \lambda_2) \).

Fig. 4. Calculations involving the dispersion of cut-off values of modes in tapered waveguide for \( n_c = 1 \).

Fig. 5. Measurement method of spectrum of the modes propagating in tapered waveguide: PR – prism coupler, P – polariser, S – lens, SP – spectrometer, and \( \lambda_0 \) is the length of the wave radiated off to the substrate at the distance \( z_0 \).
Fig. 6. Normalised transmittance values of the spectra of modes TE₀ and TM₀ propagating in the tapered waveguide for selected distance z₀ obtained from the measurements according to Fig. 5.

tral composition of the light introduced to the waveguide was reduced by the wavelength λ₀ radiated off to the substrate. The input spectrum subjected to angular distribution, using the prism coupler, was focused by means of optical lens S and analysed by means of waveguide spectrometer SP. The polariser P enabled separate analysis of the spectrum of modes TE₀ and TM₀. Figure 6 compares the normalised spectral transmittance values within the range 450–750 nm for both polarisation states as the function of distance z₀. As it had been predicted theoretically with respect to the dispersion of modes’ cut-off (Fig. 4), in the transmittance spectra for the light propagating in the form of mode TM₀, the cut-off of the waves from the red part of spectrum is taking place earlier than for the mode TE₀. Figure 7 presents the calculated, on the basis of modal Eq. (5),

Fig. 7. Calculation of modes’ cut-off values for the wave λ = 677 nm as depending on the refractive index of the waveguide’s cover.

relations between the cut-off value of modes TE₀ and TM₀ of the wave λ = 677 nm and the refractive index of the cover n_c from the interval (1.0–1.5). The calculations imply that the dynamics of the changes of cut-off value is higher in this case for mode TM₀. The changes of cut-off values are here within the range of a few millimetres. Therefore that type of waveguide can be applied as a sensor reacting to the changes of refractive index of the cover layer.

4. Conclusions

Gradient structures of tapered waveguides, in which the cut-off of modes is taking place during the propagation of light along their thickness gradient, can be applied as sensor elements detecting the changes of refractive index of the layer covering them. Making use of chromatic dispersion of cut-off values of the modes, such structures enable the analysis of absorption changes of sensor layer in a given spectral range. There are two possibilities of spectrum analysis. The first one, described in this paper for the
propagating light – whose spectral composition is the complement of the light spectrum introduced to the waveguide for the wavelengths radiated off to the substrate – requires the decoupling element (prism). The exemplary utilisation of the described phenomenon in sensor related applications with the use of monochromatic illumination for the detection of changes of refractive index of the waveguide’s cover is presented in Fig. 8. The second possibility (technically more difficult) would require the introduction of cut-off waves and their propagation in the substrate by respective cutting it down in the cut-off area of the spectrum. In that case, the cut-off spectrum would be directly subjected to analysis. The length of the area in which the cut-off of modes is taking place depends on the time and immersion depth of the substrate, so the fabrication technology of such structures is relatively simple. Further research involving the discussed problem will be concentrated on the fabrication and transmission properties of tapered waveguide strip structures.

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References

7. R. Rogożński, “Electrodiffusion processes with the conversion of polarisation direction of electric field in the formation of planar waveguide structures using ion exchange technique in glass,” Optica Appl. 28, 331–343 (1998).