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Optical waveguides produced in ion exchange process from the solutions of $AgNO_3$-$NaNO_3$ for planar chemical amplitude sensors

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The paper presents the results of studies on the production of planar optical waveguides to be applied in amplitude chemical sensors, using ion exchange technique $Ag^+ \Leftrightarrow Na^+$ *from the solutions of* $AgNO_3$-$NaNO_3$*. Substrates from BK-7 glass and from soda-lime glass were applied. The influence of the parameters of the applied technologies on the shape of refractive index profiles of the produced planar waveguides was presented. For the produced waveguides the dependence was determined between modal attenuation coefficients as the function of mode order as well as the uniformity parameters of modes reaction with absorption sensor layer.*

Keywords: optical waveguides, chemical sensors, refractive index.

1. Introduction

A very intensive development of planar waveguide chemical sensors has been observed recently. The said development is stimulated by various factors. On the one hand it is the constantly increasing demand for new measurement techniques, which can be applied to monitor the condition of natural environment, to control technological processes or detect the presence of hazardous species, and on the other hand there are the advantages which result from the application of optical waveguide technique [1,2].

Waveguide chemical sensors with internal light modulation are realized with the application of evanescent wave spectroscopy (EWS) [1–6]. Due to the lack of appropriate sensitive materials for phase sensors and, at the same time, the access to relatively great variety of sensitive materials for amplitude sensors, amplitude chemical sensors are still being developed. Absorption change of sensitive film, is the physical effect being applied in these sensors. In amplitude sensors, both single-mode [3,4] and multimode [5] waveguides can be applied. The absorption of the sensitive film in waveguide chemical sensors is the function of a wavelength. Therefore one of the conditions to obtain high sensitivity of the sensor is to ensure optimal selection of a wavelength. In general terms, this condition cannot be satisfied by the laser diodes (LD) offered on the market, and therefore the application of single-mode waveguides in chemical sensors is rather difficult. It is electroluminescence diodes (LED) which can be applied as light source in chemical sensors. Amplitude detection and available light sources as well as economical reasons speak for the application of multimode waveguides in chemical sensors with absorption sensitive film. However, multimode amplitude evanescent wave sensors are in general sensitive to the changes of launching conditions of the sensor structure.

Gnewuch and Renner demonstrated in Ref. 6 that in the waveguides of the linear profile of a refractive index, modal attenuation coefficients are independent of the mode order. For the verification of their results, the above authors used a planar optical waveguide produced in soda-lime glass obtained with the application of dissolved admixture source whose profile, however, was not linear. It was demonstrated in Ref. 7 that planar waveguides of the linear profile of refractive index can be obtained with the application of ion exchange processes carried out in the presence of alternating electric field. In planar waveguide chemical sensors, the sensor structure is coupled with fiber waveguides which are joined with light source and detector. Therefore during the sensor operation, the changes of excitation conditions of the structure can be only affected by some disturbances in the arrangement of the waveguide, principally of the bends. Then, the change of the distribution of power between the modes of higher order and lower order is taking place. Thus, in terms of intuition, it seems that the systems making use of sensor structures with the wave guides of non-monotonic distribution of attenuation can also be characterized by low sensitivity to the changes of the arrangement of waveguide fibers coupled with the sensor structures. Waveguides of such properties can be produced in ion exchange technology in glass. The above problem has been discussed in the present paper.

In the paper we present the results of investigations on the possibility of production of planar waveguides of different shapes of refractive profiles in the processes of ion exchange $Ag^+ \Leftrightarrow Na^+$ and we determine their influence on the distribution of modal attenuation.

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As the admixture source, dissolved silver nitrate $AgNO_3$ was applied in sodium nitrate $NaNO_3$, and two types of glass substrate were used, BK-7 glass and soda-lime glass. For the produced planar waveguides, the dependence of attenuation coefficients on a mode order was determined as well as reaction uniformity parameters. The problems involving the production of waveguides with the use of dissolved admixture source have not been in detail discussed in literature so far. To the best of our knowledge, the influence of technological parameters and of the shape of refractive index profile on the distribution of modal attenuation has not been discussed in literature so far.

2. Structure of planar sensor

A typical structure of planar evanescent wave amplitude chemical sensor is presented in Fig. 1. On the waveguide *W* there is an absorption sensor layer *C* which is being penetrated by evanescent field of modes propagating in the structure. As a result of the reaction of the chemical species on the sensitive film, changes of its absorption are taking place, and consequently the changes of the amplitude of the transmitted modes. If coupling of modes in the structure is not taking place, then for each of them the law of Lambert-Beer can be written in the following form

$$P_m = P_{0m} \exp(-\tilde{\gamma}_m n^{(i)} x) \tag{1}$$

where m stands for the mode order, P_{0m} and P_m stand for power of the m-th mode respectively at the input and output of the structure of the length x, $\tilde{\gamma}_m$ is the normalized attenuation coefficient of the m-th mode, $n^{(i)}$ is the imaginary part of the refractive index of a sensitive film.

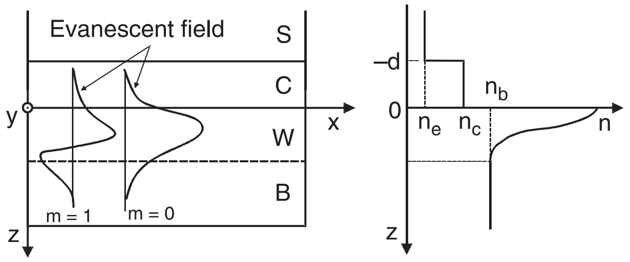
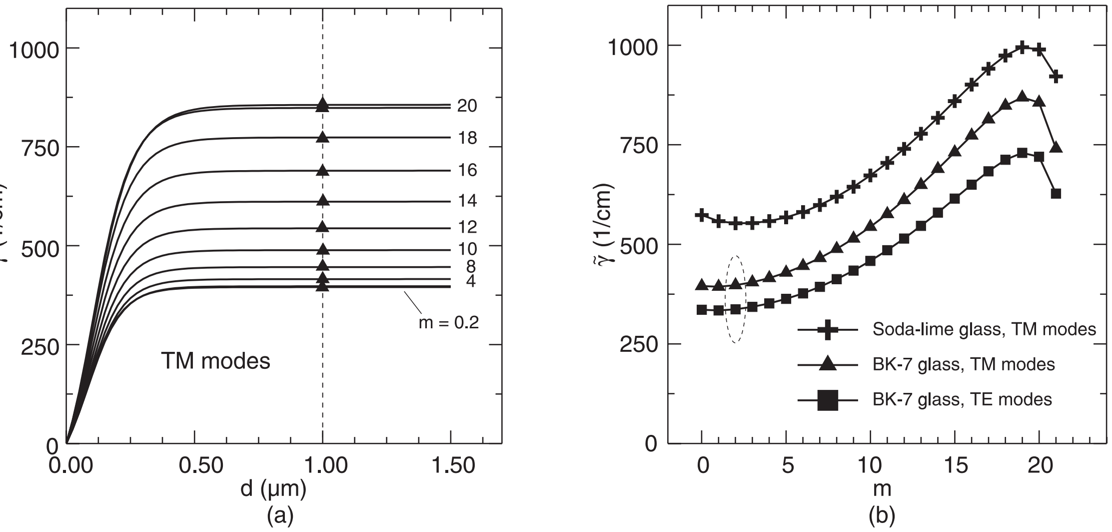


Fig. 1. Scheme of planar structure. B – substrate, W – gradient waveguide, C – sensitive film, S – surroundings.

The normalized attenuation coefficients $\tilde{\gamma}_m$ of modes were determined using the expression formulated by Snyder and Love in Ref. 8. The effective refractive indices of modes needed here and the distribution of modal fields were determined making use of a matrix method 4×4 [9,10]. As it was demonstrated in Ref. 11, using this method we can very accurately determine modal parameters of the investigated waveguides. In the analysis, absorption covers of the finite thickness *d* were considered. For the analyzed structures, dependencies were determined involving normalized attenuation coefficients on sensitive film thickness *d* and normalized attenuation coefficients on a mode order. In all calculations whereof the results are presented in the work, the parameters of sensitive to ammonia films produced by the authors in sol-gel technology were taken into consideration [12]. Hence, the calculations were carried out for the wavelength $\lambda = 600$ nm, corresponding with maximum sensitivity of the film. The refractive index of the film is $n_c = 1.44$. For the sake of comparison, in the theoretical analysis, the waveguides having the same number of modes for a given substrate were considered.

Exemplary characteristics which have been obtained in the analysis are presented in Fig. 2. Figure 2(a) presents a family of characteristics corresponding with TM modes of even order in the structure produced with the use of the waveguide obtained in ion exchange $Ag^+ \Leftrightarrow Na^+$ in BK-7 glass, when non-dissolved admixture source is applied. It



(a) (b)

Fig. 2. Dependence of normalized attenuation coefficients: (a) on the thickness of sensor layer for the waveguide produced in glass BK-7, (b) on mode order for the waveguides produced in soda-lime glass and in BK-7 glass for sensitive film thickness d = 1.0 μm.

can be seen from the presented relations that the normalized attenuation coefficients $\tilde{\gamma}$ strongly depend on the thickness d of a sensor layer. Initially, when the thickness of a sensitive film is growing, strong increase in normalized attenuation coefficients is observed. It is the result of the increase in the evanescent field power in the sensitive film. When the films thickness reaches the value comparable to the penetration depth of evanescent field, then the dependence of normalized attenuation coefficients on the film thickness is changing more slowly until it reaches constant value for the thickness d higher than the penetration depth of an evanescent field. We can observe that the relations $\tilde{\gamma}_m(d)$ are different for different modes. It is particularly evident in Fig. 2(b) where the dependence of normalized attenuation coefficients on a mode order was presented for the same waveguide, for both polarizations TE and TM when the thickness of sensitive film $d = 1.0$ μm. For the sake of comparison also the characteristic corresponding to TM modes in the waveguide produced in soda-lime glass was presented. As it can be seen from the comparison of the relations for both types of substrate, their qualitative character is similar, which is the effect of similar shapes of refractive index profiles of waveguides obtained in BK-7 glass and in soda-lime glass. In the further part of the work we will show that the modal distributions of attenuation coefficients depend on the shape of refractive index profiles of the waveguides.

From the viewpoint of application potentials in amplitude chemical sensors, possibly the most uniform reaction of modes with absorption sensitive film is desirable. Then the sensor structure will have low sensitivity to the changes of launching conditions. In order to compare the reaction uniformity of the modes with absorption layer in sensor structures with different refractive index profiles of waveguides, we will use the parameter of reaction uniformity defined in the following way

$$\chi = \frac{\delta\tilde{\gamma}}{\langle\tilde{\gamma}\rangle}100\% \qquad (2)$$

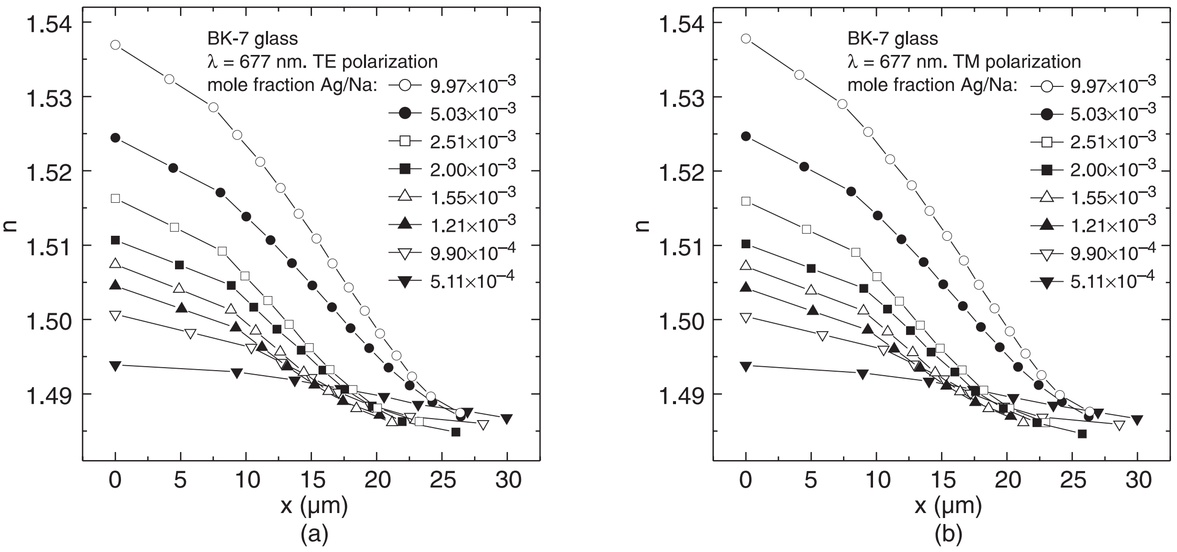
where $\delta\tilde{\gamma}$ is the average deviation of normalized attenuation coefficients $\tilde{\gamma}_i$ from the average value and $\langle\tilde{\gamma}\rangle$ is the average value of normalized attenuation coefficients $\tilde{\gamma}_i$.

3. Technology and measurements

Great potentials involving the production of waveguides having different shapes of refractive index profile are offered by the application of ion exchange in glass [13,14]. One of the aspects of studies presented here is to show the possibilities involving the shaping of refractive index profiles offered by the processes of thermal diffusion carried out in melted mixtures of solutions $AgNO_3$- $NaNO_3$. In the studies presented in Ref. 15, the authors proved the possibility to apply the solutions $AgNO_3$- $NaNO_3$ giving notice only of the changes of the maximum value of refractive index in the obtained planar waveguides structures. The studies carried out by us have showed that the change of admixture source composition, from which the diffusion process is carried out, influences also the shape of the final profile. In this way we can, in a relatively simple way, influence the shape of refractive index profile of the waveguide produced from the dissolved admixture source, and hence to influence the distribution of modal attenuation.

3.1. Technological processes

The research was concentrated on waveguides produced in the glass substrates: BK-7 (Schott) and soda-lime (Microscope Slides, Menzel-Glaser). We focused our studies on the waveguides produced with the use of dissolved admixture sources $AgNO_3$-$NaNO_3$ of different molar ratios within the range of 2.76×10^{-4}–9.97×10^{-3}. The temperatures of the pro-



(a) (b)

Fig. 3. Refractive index profiles of waveguides produced in BK-7 glass for different mole fractions Ag/Na of admixture source. Profiles for wavelength $\lambda = 677$ nm, polarization states: (a) TE, (b) TM.

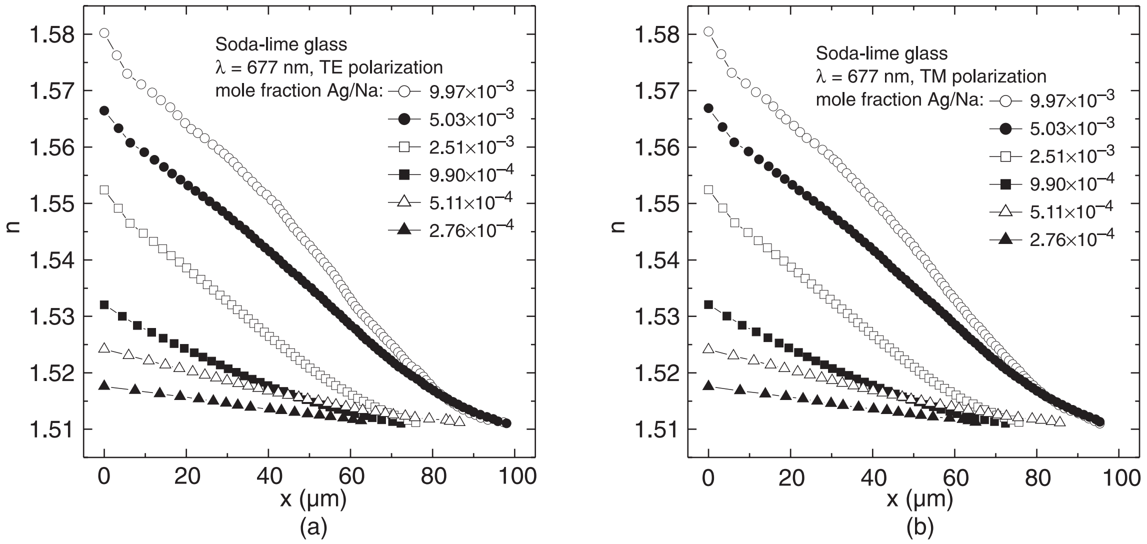


Fig. 4. Refractive index profiles of waveguides produced in soda-lime glass for different mole fractions Ag/Na of admixture source. Profiles for wavelength $\lambda = 677$ nm, polarization states: (a) TE, (b) TM.

cesses were 380°C. Refractive index profiles of the produced waveguides were obtained basing on the measurements of propagation constants of waveguide modes with the use of modal equation [16], for wavelength $\lambda = 677$ nm. Effective refractive indices of modes were determined with the accuracy not lower than 0.0003. In order to define the shapes of the obtained refractive index profiles more accurately (for the reconstruction of the profile a large number of modes are needed), the technological processes were realized over long time periods of around several dozen hours. To ensure that the concentration and mixing temperature of salts was homogeneous, mixing of the solution during the process was maintained. Due to low concentration of silver ions in the mixture, to ensure constant output of the source over long time period in which the process was being carried out – great volumes of solutions were applied. Mole fraction of the mixture in the solution $AgNO_3$-$NaNO_3$ was determined with the uncertainty lower than 2.5×10^{-5}. The temperature of melted salt inside the crucible was recorded during the process. The parameters of technological processes realized in BK-7 glass are presented in Table 1. In soda-lime glass six waveguide structures were produced. The parameters of the carried out technological processes are presented in Table 2. Refractive index profiles of the waveguides produced in BK-7 glass are presented in Fig. 3. Figure 4 presents the refractive index profiles of waveguides produced in soda-lime glass. We can observe, comparing the refractive index profiles (Figs. 3 and 4) obtained for both polarizations (TE, TM), that within the applied concentrations of admixture sources, the phenomenon of birefringence is not taking place in the produced waveguides.

It can be seen from the comparison of the depths of refractive index profiles and the obtained maximum increase in the refractive index Δn_s, in both types of substrate, that in the soda-lime glass the kinetics of exchange processes is higher than in BK-7 glass.

Table 1. The parameters of technological processes realized in BK-7 glass.

BK-7 glass: $n_{b\,677} = 1.5131$							
Sample	Ag/Na [mole fraction]	Temperature of diffusion [°C]	Duration of diffusion [h]	Number of modes		$\Delta n_{(TE)}$	$\Delta n_{(TM)}$
				TE	TM		
1	5.11e-4	385±2	49.5	7	7	0.0038	0.0038
2	9.90e-4	382±2	24	7	7	0,0072	0,0071
3	1.21e-3	385±2	24	7	7	0,0092	0,0091
4	1.55e-3	385±2	24	8	8	0,0106	0,0105
5	2.00e-3	385±2	24	8	8	0,0107	0,0107
6	2.51e-3	382±2	24	10	10	0,0151	0,0149
7	5.03e-3	382±2	24	13	13	0,0191	0,0193
8	9.97e-3	382±2	24	15	14	0,0254	0.0258

Table 2. The parameters of technological processes realized in soda-lime glass.

Soda-lime glass: $n_{b\ 677}$ = 1.5111							
Sample	Ag/Na [mole fraction]	Temperature of diffusion [°C]	Duration of diffusion [h]	Number of modes		$\Delta n_{(TE)}$	$\Delta n_{(TM)}$
				TE	TM		
1	2.76e-4	382±2	49.5	17	18	0.0066	0.0065
2	5.11e-4	382±2	49.5	31	31	0.0132	0.0131
3	9.90e-4	382±2	24	32	32	0.0211	0.0211
4	2.51e-3	382±2	24	48	48	0.0414	0.0414
5	5.03e-3	380±2	24	74	73	0.0554	0.0559
6	9.97e-3	380±2	24	82	82	0.0692	0.0695

3.2. Changes of refractive index

From the viewpoint of production technology of waveguide structures with the use of dissolved admixture sources, it is important to define influence of the mole fraction κ of admixture ions in the source on the obtained change of refractive index of the waveguide. In the process of two-component ion exchange, admixture ions are introduced to glass (ions of type A) and modifier ions are leaving the glass (ions of type B). This process is described by means of space-time changes of the concentration of these c_A and c_B ions. Equilibrium concentration is determined as $c_0 = c_A + c_B$, which, for pure glass (without admixture), satisfies the condition $c_0 = c_B$. In ion exchange processes, the obtained change of the value of refractive index is proportional to the concentration of the admixture c_A introduced to glass [17]. In the case of diffusion processes, the maximum change of refractive index is taking place on glass surface

$$\Delta n_{max} = \Delta n_s = \beta c_{Amax} \tag{3}$$

where Δn_s is the change of refractive index on glass surface and β is the factor of proportionality.

In the ion exchange processes realized in this work, Ag^+ ions are of A type, and Na^+ ions are modifier ions in glass. The kinetics of the ion exchange process, taking place along the phase border glass-melted salt can be written using the equilibrium constant $\boldsymbol{K}$ [17].

Defining the mole fraction of Ag^+ ions in the solution $AgNO_3$-$NaNO_3$ as

$$\kappa = \frac{c^m_{Ag}}{c^m_{Ag} + c^m_{Na}} \tag{4}$$

where c^m_{Ag}, c^m_{Na} is the concentration of ions Ag^+ and Na^+ in a source solution.

We can express the maximum change of refractive index on the glass surface Δn_s [Eq. (3)] using equilibrium constant of the exchange process $\boldsymbol{K}$ and the mole fraction κ [18]

$$\Delta n_s(\kappa) = \beta c_0 \frac{\boldsymbol{K}\kappa}{\boldsymbol{K}\kappa + 1 - \kappa} \tag{5}$$

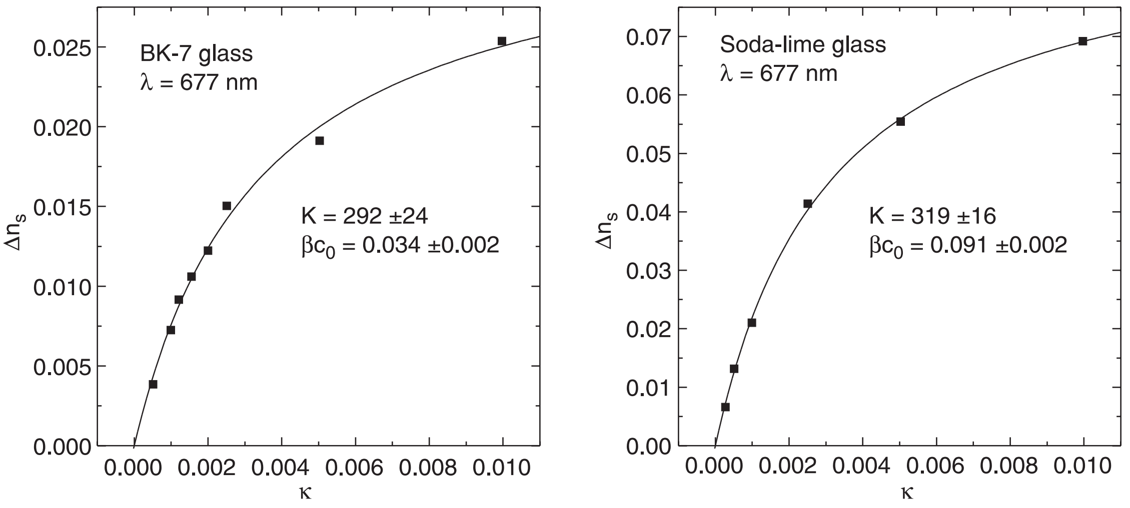
By determining the change of refractive index on the glass surface Δn_s as the function of mole fraction of silver in the solution $AgNO_3$-$NaNO_3$, we can match Eq. (5) to the obtained set of points $\{\Delta n_s, \kappa\}$, assuming the values $\boldsymbol{K}$ and βc_0 as matching parameters. By doing so we can determine equilibrium constant of ion exchange processes for a given system glass-admixture. Figure 5 presents the relations $\Delta n_s(\kappa)$ determined from the measurements of refractive index profiles of the produced waveguides in glass: soda-lime and BK-7 for TE polarization (Tables 1 and 2). The theoretical curves obtained as the best matching to the measurement points were achieved when the equilibrium constant $\boldsymbol{K}$ = 319 ±16 for soda-lime glass and when $\boldsymbol{K}$ = 292 ±24 for BK-7 glass. The determined equilibrium constants can be used to design maximum changes of refractive index with the application of other mixtures of the compositions dissolved in the given types of glass. It can be seen from the presented relations that the obtained changes of refractive index Δn_s strongly depend on the mole fraction κ, in particular within the range of its small values. With the increase in mole fraction of the admixture in the source solution, the dependence $\Delta n_s(\kappa)$ is getting weaker.

3.3. Analysis of a shape of refractive index profile

The refractive profile of gradient planar waveguide for a given wavelength is presented by the equation [19]

$$n(z) = n_b + \Delta n_s u(z) \tag{6}$$

where n_b is the refractive index of the substrate, Δn_s is the maximum change of the refractive index on the substrate surface, and $u(z)$ is the normalized concentration of the admixture (A type ions) introduced into glass.



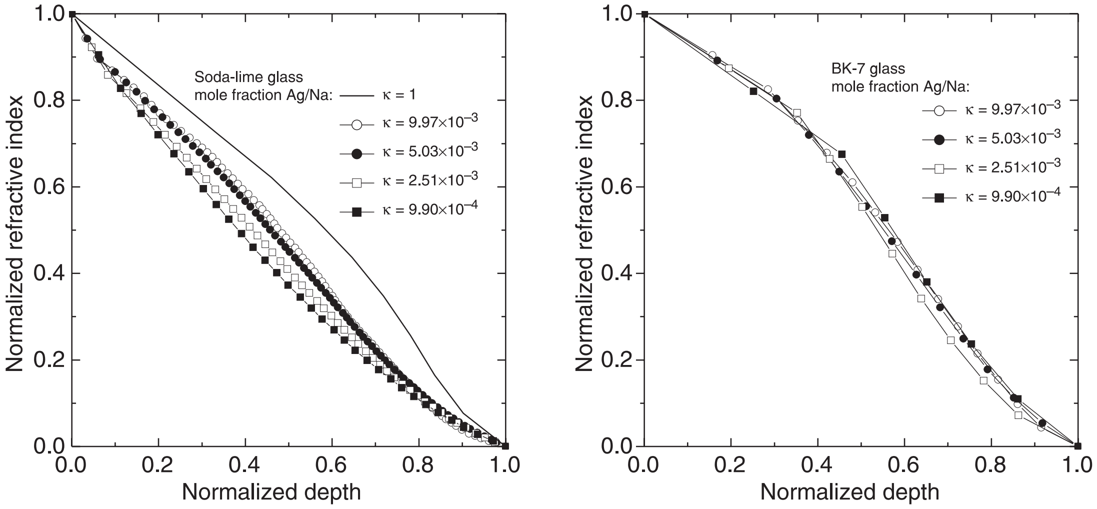
(a) (b)

Fig. 5. Dependence of the change of refractive index on glass surface on the mole fraction of silver nitrate in the solution $AgNO_3$-$NaNO_3$ for waveguides produced in glass: (a) BK-7, (b) soda-lime.

By the term ‘the shape of refractive index profile’ we understand both the run of function $n(z)$ describing one-dimensional refractive index profile (function $u(z)$) and the produced changes of refractive index Δn_s.

The shapes of refractive index profiles of waveguides produced from the solutions $AgNO_3$-$NaNO_3$ show dependence on the mole fraction defined by Eq. (4). In the produced waveguides this dependence is explicit for soda-lime glass (Fig. 4). We can see there the influence of on the character of profile run: from the convex for high values of κ to concave with low κ. In order to ensure better comparison involving the change of the character of the shapes of refractive index profiles they were normalized on both axes of the graph. The obtained results for soda-lime glass is presented in Fig. 6(a). The occurring here explicit dependence of the character of refractive index profile shape on the bath composition of admixture source is the result of the dependence of ion exchange on glass surface on κ.

For the sake of comparison, in Fig. 6, solid line was used to mark normalized profile of the waveguide produced in pure $AgNO_3$ ($\kappa = 1$). Convex shape of such a refractive index profile be speaks of small mobility ratio μ_A/μ_B of the ions exchanged in glass [14]. The decrease in the concentration c_A of the introduced admixture in the area near glass surface, being the dissolution result of the admixture source bath (value κ), brings about in this case the situation where the output of admixture source is limiting the exchange process in glass. Through an appropriate selection of admixture source composition it is possible in this way to produce a refractive index profile of the run similar to linear. It can be observed from the presented results that such a profile will be representative for the wave-



(a) (b)

Fig. 6. Influence of the mole fraction of silver nitrate in the solution $AgNO_3$-$NaNO_3$ for waveguides on normalized refractive profiles in case: (a) soda-lime glass, (b) BK-7 glass.

guide produced from the admixture source of the mole fraction being within the range $2.51\times10^{-3} < \kappa < 5.03\times10^{-3}$.

In the case of BK-7 glass substrate [Fig. 6(b)] no distinctive change involving the run of the character of refractive index profiles is observed as dependent on the composition of admixture source bath. For this kind of glass, ion exchange processes are taking place much slower than in soda-lime glass and the output of admixture source has, in this, case inconsiderable influence on the exchange kinetics and in consequence on the obtained refractive index profiles.

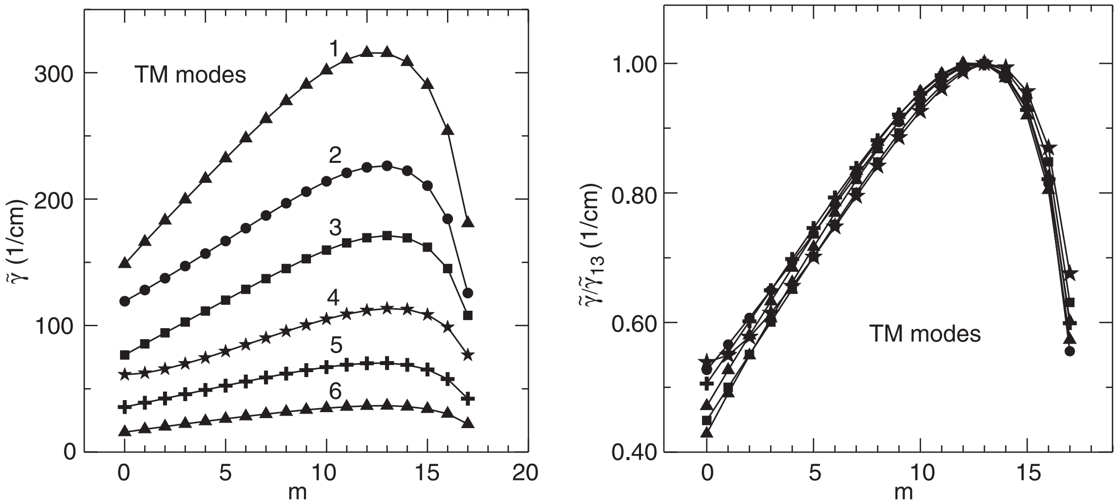
4. Analysis of sensor structure

All refractive index profiles of waveguides which were used in the theoretical analysis are the profiles of real planar waveguides. In the experimental part of the studies described above, for the produced planar waveguides, their refractive index profiles were determined, from which, by matching the solutions of diffusion equations [7], refractive index profiles were generated which had been used in the analysis. The depth of each profile was chosen in the way so that in each case the same number of modes could be obtained, which for the waveguides in BK-7 glass was 18 and in soda-lime glass it was 22. In the calculations involving mean values of normalized attenuation coefficients $\tilde{\gamma}$ and of modes reaction uniformity, always the mode of the highest order being the closest to cut-off was disregarded. The estimated uncertainty of the value of the parameter of modes reaction uniformity in the carried out analysis is 1.5%. It results from measurement accuracy when determining real refractive index profiles of the waveguides and from matching accuracy of the parameters of ion exchange processes.

As it has been mentioned above, the theoretical analysis was carried out with the assumption that sensitive films have finite thickness d = 1.0 µm, refractive indices n_c = 1.44, and the accepted wavelength λ = 600 nm corresponded with the maximum sensitivity of the sensitive to ammonia films produced by us [12]. Therefore all refractive index profiles accepted for the calculations were scaled into the wavelength λ = 600 nm.

4.1. BK-7 glass

The distributions of the normalized attenuation coefficients on a mode order for the structures with the waveguides produced in BK-7 glass are presented in Fig. 7(a). Particular dependencies correspond with different mole fractions of the mixture $AgNO_3$-$NaNO_3$, used in the ion exchange process as admixture source. These relations are non-monotonic. Initially, together with the increase in mode order, until the 13-th order mode, the increase in normalized attenuation coefficients is observed. For higher order modes, normalized attenuation coefficients are decreasing. The run of modal attenuation distribution is the consequence of the shape of refractive index profile and of the location of turning points of particular modes. As it has been presented in Ref. 20, if turning points of the modes are placed in the area in which the refractive index profile has the character of convex function, then, together with the increase in mode order its attenuation is increasing. If turning points of the modes are in the area in which the refractive index profile has the character of concave function, then the attenuation is decreasing with the increase in mode order. And hence, the character of the relation $\tilde{\gamma}(m)$ presented in Fig. 7 results from the refractive index profiles presented in Fig. 6(b). All relations shown in Fig. 7(a) are of similar qualitative character. It is illustrated in Fig. 7(b) where the same relations as in Fig. 7(a) are presented, but in each case they are reduced to a unit value for the mode of the highest value of normalized attenuation coefficient. Relative



(a) (b)

Fig. 7. (a) Distribution of modal attenuation coefficients for the structures with waveguides in glass BK-7, corresponding with different mole fractions of admixture source: (1) $\kappa = 0.00997$, (2) $\kappa = 0.00503$, (3) $\kappa = 0.00251$, (4) $\kappa = 0.002$, (5) $\kappa = 0.00099$, (6) $\kappa = 0.00051$. (b) Dependence of normalized attenuation coefficients on mode order.

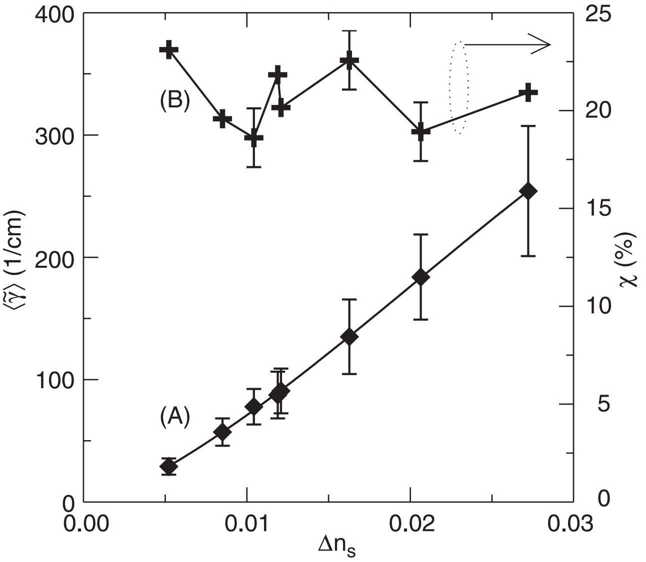


Fig. 8. Dependence of the mean value of normalized attenuation coefficients (A) and reaction uniformity (B) on the produced increase of refractive profile in waveguides produced in BK-7 glass.

changes of normalized attenuation coefficients are similar. As it can be seen in Table 1 and in Fig. 6(a), the application of admixture source of the higher mole fraction of $AgNO_3$-$NaNO_3$ brings about higher increase in refractive index on the surface of the obtained waveguides. It has also the influence on the values of normalized attenuation coefficients. It is illustrated in Fig. 8. In this figure, points were used to mark the dependence of average values of normalized attenuation coefficients on the maximum change of refractive index in the waveguide. The bars do not stand here for measurement errors and their length corresponds with the value of average deviation of the normalized attenuation coefficients $\tilde{\gamma}_i$ from the average value. The determined from that values of reaction uniformity parameter χ is within the range from 18.7% to 23.1% and they do not show any pronounced dependence on Δn_s. They are presented in Fig. 8 in a graphical form. Here, the bars stand for uncertainty of the value of the parameter of modes reaction uniformity $\Delta\chi = 1.5\%$.

4.2. Soda-lime glass

As it was presented in chapter 3 of this work, ion exchange processes carried out in soda-lime glass are characterized by the higher kinetics than in BK-7 glass. Therefore when using this substrate we obtain different, in terms of quality, refractive index profiles which are dependent on mole fraction of admixture source in the solution $AgNO_3$-$NaNO_3$. These profiles can be further modified in the processes of thermal heating. We present below the distributions of modal attenuation for the waveguides obtained in diffusion processes and for the waveguides subjected to heating.

4.2.1. Diffusion

Figure 9 presents the distributions of modal attenuation coefficients $\tilde{\gamma}(m)$ determined for different mole fractions of the admixture in the source solution $AgNO_3$-$NaNO_3$. These distributions, in contrast to the ones presented in Fig. 7(a) for BK-7 glass, show considerable qualitative differences. For the smaller mole fractions κ, normalized attenuation coefficients are decreasing with the increase in a mode order. As it follows from the regularity presented earlier, it is typical for concave refractive index profiles. For the higher values of κ, the obtained relations $\tilde{\gamma}(m)$ have non-monotonic character, which is the effect of different shapes of refractive index profiles corresponding to them [Fig. 6(a)]. Figure 10 presents the values of average normalized attenuation coefficients as the function of maximum change of refractive index in the waveguide. The determined here values of reaction uniformity parameter χ are within the range from 11% to 17%. They are presented in a graphical form in Fig. 10. They are in this case distinctly smaller than the ones determined for the structures with the BK-7 glass substrate. It means that the sensor structures made with the application of waveguides produced in soda-lime glass will be characterized by the lower sensitivity to the changes of optical excitation conditions. At the same time, as it follows from the runs presented in Figs. 8 and 10, in the latter case the higher mean values of normalized attenuation coefficients are obtained, which means that these structures are offering potentially higher sensitivity to the absorption change of sensor layer affected by the reaction of monitored chemical species.

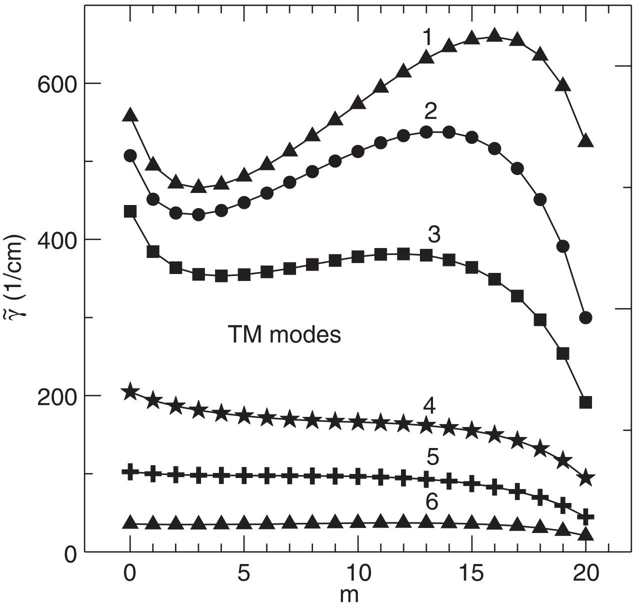


Fig. 9. Dependence of normalized attenuation coefficients on mode order for the waveguides in soda-lime glass, corresponding to different mole fractions of admixture source: (1) $\kappa = 0.00997$, (2) $\kappa = 0.00503$, (3) $\kappa = 0.00251$, (4) $\kappa = 0.00099$, (5) $\kappa = 0.000511$, (6) $\kappa = 0.000276$. TM polarization, sensitive film thickness d = 1000 nm.

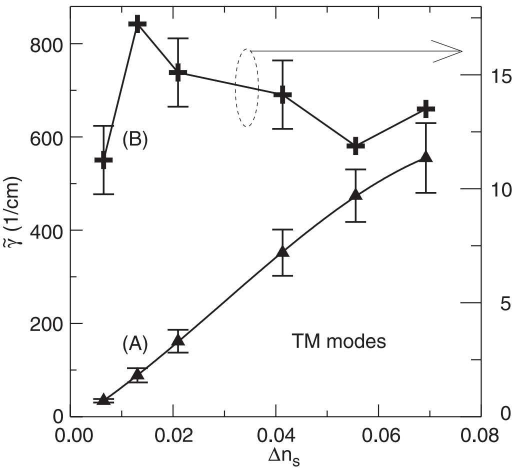


Fig. 10. Dependence of mean value of normalized attenuation coefficients (A) and reaction uniformity (B) on the produced increase of refractive index in the waveguides produced in soda-lime glass.

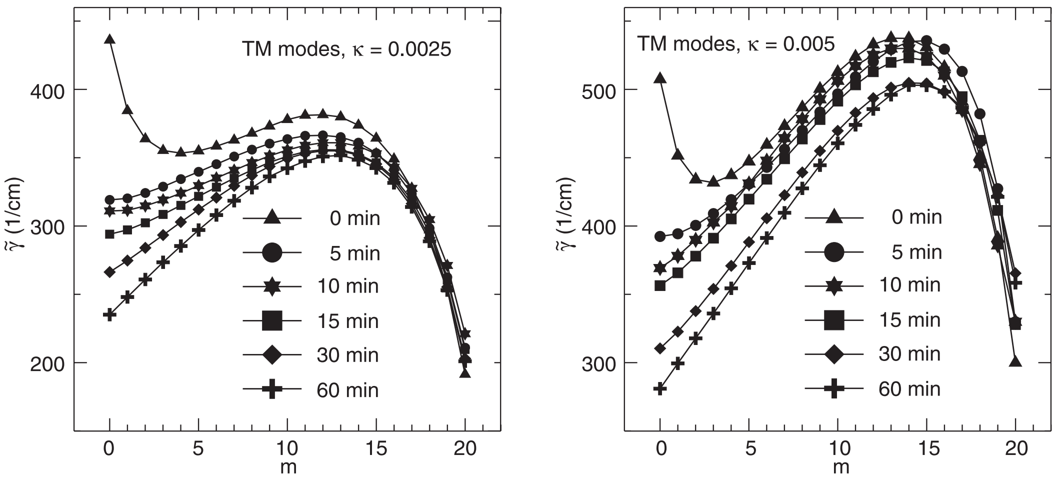
4.2.2. Heating

Heating of waveguides produced in ion exchange is a technological process which allows us to modify the refractive index profiles produced earlier. Within the scope of the carried out studies, we determined the influence of heating processes of planar waveguides produced from dissolved admixture sources on the distribution of modal attenuation coefficients and on the reaction uniformity of modes with an absorption cover. All heating processes were carried out at temperature 380°C. Figure 11 presents the distribution of modal attenuation coefficients corresponding with different heating times of the waveguide produced from the solution of $AgNO_3$-$NaNO_3$ of the mole fraction respectively κ = 0.0025 [Fig. 11(a)] and κ = 0.005 [Fig. 11(b)]. For each case we can see the influence of heating time on the distribution of modal attenuation coefficients. The strongest changes are taking place for the modes of the lowest order. Similar changes were obtained for the concentration of source solution κ = 0.01.

The influence of heating time of the produced waveguides on the reaction uniformity of modes with absorption cover, for different mole fractions of source solutions, is presented in Fig. 12. The lowest value of the reaction uniformity parameter χ for the waveguide which was not subjected to heating was obtained from the source solution of the mole fraction κ = 0.005. In the structure with the waveguide produced from the solution of the mole fraction κ = 0.0025, short heating of the waveguide (10 min) radically lowers the value of the parameter χ (from 14.2% to 9.6%). Further heating results in the increase in the parameter χ, which means that there is a deterioration of reaction uniformity of modes with absorption cover. As it follows from the presented results, when the heating times are growing, then the parameter χ, for the structures with waveguides produced from source solutions of the higher concentration of admixture (κ = 0.01 and κ = 0.005) is approaching the values which were obtained for the structures with waveguides produced in BK-7 glass. The highest uniformity from among the investigated waveguides should be offered by the structure made on the waveguide produced in soda-lime glass, from the source solution of mole fraction κ = 0.0025, and then heated over 10 min at temperature 380°C. The application of such a waveguide in the structure of multimode amplitude chemical sensor may guarantee low sensitivity of the structure to the changes of optical excitation conditions. The calculations carried out for this waveguide demonstrate that the thickness of absorption layer of the cover does not influence the parameter of modes reaction parameter χ.

5. Conclusions

The paper presents two aspects involving the production of planar waveguide structures using the technique of ion exchange from solutions.



(a) (b)

Fig. 11. Influence of waveguide heating on the distribution of modal attenuation coefficients.

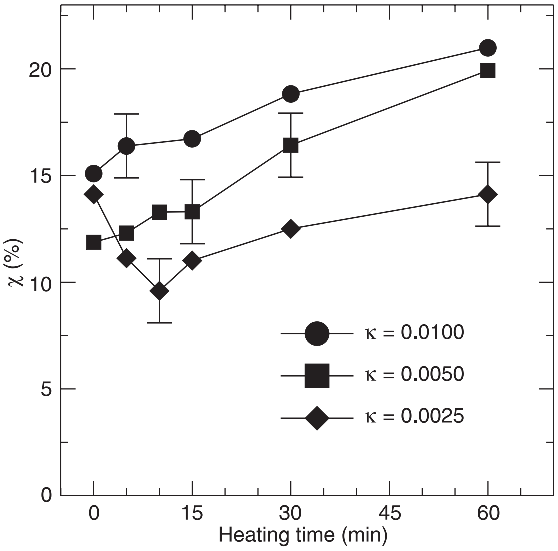


Fig. 12. Influence of heating times on the reaction uniformity of modes with absorption cover.

The first aspect of the work involves the possibility to influence the shape of the obtained refractive profile through an appropriate selection of Ag^+ ions in admixture source. We have presented the methods to obtain different shapes of refractive index profiles in soda-lime glass. In glass BK-7, the change of admixture source composition has no influence on the shapes of the obtained refractive index profiles. For the investigated waveguides, the phenomenon of double refraction within the applied concentrations of admixture source has not been found. For both applied types of a base we provided equilibrium constants defining the kinetics of ion exchange processes.

The second aspect of the paper involves the influence of the shape of the refractive index profile of the waveguide on the distribution of modal attenuation in the structures with absorption cover. It has been demonstrated for the first time, that for refractive index profiles which in some intervals have the character of convex function and concave function, the distributions of modal attenuation have non-monotonic character. The highest modes reaction uniformity with absorption cover, from among the investigated ones, has the waveguide produced in soda-lime glass from the solution $AgNO_3$-$NaNO_3$ of molar ratio $\kappa = 0.0025$, which was then subjected to short heating. For this waveguide the parameter of modes reaction uniformity with absorption cover was $\chi \approx 10\%$.

The presented results of investigations indicate that it is possible to apply a simple technology of waveguide production from dissolved admixture sources for amplitude chemical sensors having low sensitivity to the change of excitation conditions.

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