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Refractive index profiles of planar waveguides produced in electrodiffusion processes

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The paper presents the results of investigation which demonstrate the possibilities to shape refractive index profiles of planar waveguides produced in glass using the ion exchange technique with the application of electrodiffusion processes with the change of direction of electric field polarization. We also attempted to determine equilibrium concentration of mobile glass ions based on the value of electric charge passing through glass in the electrodiffusion process.

Keywords: planar waveguides, field-assisted ion-exchange.

1. Introduction

Waveguide structures produced in glass bases with the application of ion exchange technique have been used in planar optoelectronics for many years. The technologically simplest form of this technique consists in the application of thermal activation of dopant ions introduced to the glass base from liquid source. Due to the concentration gradients of the said ions present in the surface area of glass, this process has a purely diffusive character. The refractive index profiles of waveguides obtained in this way have the shape determined by the ratio of the mobility of dopant ions to the mobility of glass ions subjected to the exchange [1]. The situation changes considerably when during the diffusive exchange process to glass substrate the external electric field is applied. Such processes referred to as electrodiffusion processes have been described in many publications whereof the work of Izawa and Nakagome from the year 1972 is considered to have been one of the earliest [2].

In processes of that type, the distribution form of dopant introduced to glass c_a, is dependent on the mutual relation between the diffusive component $D_a \nabla c_a$ and the component of electric migration $\mu_a c_a \mathbf{E_0}$ [3], [4] (D_a, μ_a denote diffusion constant and electric mobility of ions introduced into the glass, respectively, $\mathbf{E_0} = \mathbf{E_d} + \mathbf{E}$ is the intensity of local electric field). The local electric field is a superposition of diffusion field $\mathbf{E_d}$ being the result of the difference between the mobility of exchange ions and external field $\mathbf{E}$ [5]. As a result, we can stimulate the distribution of dopant being

formed in the glass through a respective selection of both the value and the direction of the external electric field polarization **E**. The idea involving the application of cyclic polarization change of electric field in electrodiffusion processes has been described in paper [6]. The authors pointed to a theoretical possibility of influencing the final form of refractive index profile of a waveguide in electrodiffusion processes, during which multiple change of direction of electric field polarization was applied. Some of the results have been confirmed experimentally.

Electrodiffusion processes with the application of liquid dopant sources are quite troublesome in practical realization since it is necessary to ensure perfect electric insulation of the dopant source at relatively high temperatures. But their advantage lies in the possibility of obtaining various shapes of refractive index profiles which cannot be done in purely thermal diffusion processes. This problem becomes important in production of waveguide structures for which the shape of refractive index profile of waveguide line is relevant.

In this work, we present the results of experimental investigation of the possibility of influencing the final shape of refractive index profile of planar waveguides produced in electrodiffusion processes with the fixed or changed direction of external electric field polarization [7]. In Sec. 2, a special stand for use in the electrodiffusion processes has been described. Section 3 describes technological processes. The experimental results involving the measurements of refractive index profiles of the waveguides produced are presented in Sec. 4. Section 5 presents the relationship between the change of refractive index and the value of electric charge flowing during the process. Section 6 contains summary and conclusions.

2. Technological stand

Technical realization of the electrodiffusion process is rather complicated. The basic difficulty lies in the fact that perfect electric insulation must be ensured on both sides of glass substrate, and they at the same time must have contact with the liquid phase of dopant source, which is made up by nitrates (most frequently silver and potassium ones, and their mixtures) – which are strong oxidizers. Such processes are realized at temperatures of 200–400°C.

The propositions of technical solutions to this problem involve a construction of a vessel having an appropriate shape filled with melted salt and immersed in a crucible also containing melted salt [3]. Electric field is produced by immersing appropriate electrodes in both vessels. Electrodiffusion processes are then running through all the walls of the vessel. Such a solution ensures that both surfaces of glass sample are effectively electrically insulated from each other. The basic disadvantage of this solution is that it requires appropriate glass vessels to be prepared with suitable surfaces and definite homogeneity of glass.

There are also other solutions where special preparation of glass profiles is not necessary [8], [9]. In such a case, flat substrate plates are placed and fixed between

two crucibles with melted liquid dopant. Appropriate sealing is ensured here by teflon washers or silicone. With this solution it is easy to prepare the base, which is definitely an advantage. But in each case the salt filling the vessel melts, reaching a required temperature after some definite time. The processes of thermal diffusion running during that time result in the formation of introductory, difficult to define distribution of dopant in glass. In the solution presented in work [10], a strict control of start-time of the process was ensured. Yet, in this case the electrodiffusion process could only take place in one direction since the liquid dopant source was only on one side of the base. Further improvement, consisting in the application, on both sides of flat base, of liquid dopant sources, together with the control of start-time of the process is presented in work [11]. In the solution proposed in this work, where two symmetrical crucibles are applied, it is possible to apply two liquid electrodes on both sides of glass plate. In this way electrodiffusion processes can be carried out with the change of direction of electric field polarization. Applying the same type of melted salt in both crucibles we can obtain at the same time two waveguide structures on both sides of substrate glass. The active area of base in which the electrodiffusion process is taking place can be up to 2×5 cm, which is sufficient for applications in integrated optics.

A schematic section of the technological stand is presented in Fig. 1. The melted salt being the source of the dopant introduced to glass is in two separate vessels inside

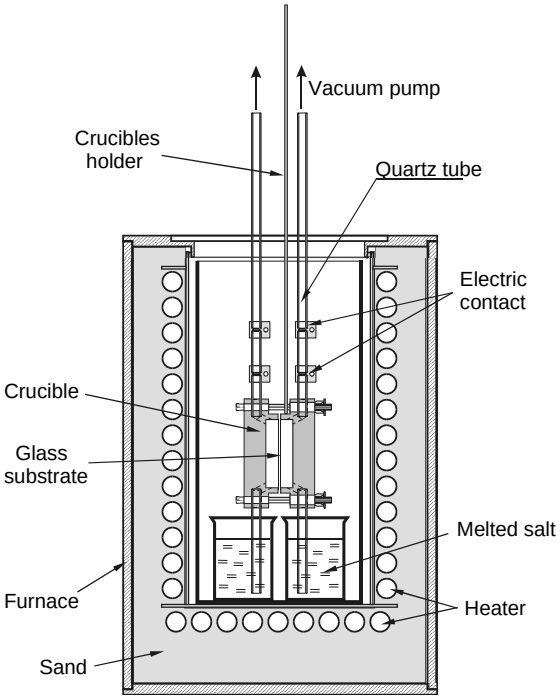

Fig. 1. Intersection of stand for electrodiffusion processes.

the furnace. Salt temperature is controlled by means of a thermocouple. The most relevant part of the stand is made up by a system of two symmetrical crucibles made from aluminum alloy between which there is a fixed, glass, substrate plate. The sealing between the glass and both crucibles consists of silicone paste resistant to temperatures of up to 350°C. Both crucibles are fixed on a special handle ensuring their precise movement into the furnace. The crucibles are joined with quartz pipes whereof ends on one side are being immersed into the melted salt, and the other ends, outside the furnace, are connected with a vacuum pump. Each crucible is connected to a wire supplying power from a feeder. The temperature of crucibles is monitored by thermocouples. The fixing of substrate plate between the crucibles is done outside the furnace. Using special clamps, it is easy to disconnect the crucibles fast and take out the substrate plate after the process has finished. After the insertion of crucibles into the furnace chamber, the glass substrate has no contact with the melted salt until an appropriate temperature (the same as that of the melted salt) has been reached by both crucibles. As a result of the underpressure produced the salt is sucked into both crucibles. In this way, there is melted salt, being the liquid source of dopant on both sides of the glass substrate plate. Applicatying appropriate polarization of the crucibles it is possible to carry out the electrodiffusion process during which we can freely change both the direction of polarization and the value of voltage applied to the crucibles. During the process we can record the value of electrical current flowing through the glass substrate. Using special contacts fixed on quartz pipes joining both crucibles with the vacuum pump, we can control the level of melted salt sucked into both crucibles. After the process has been finished, the vacuum pump is switched off and the melted salt returns to the vessels inside the furnace, and both crucibles are immediately taken out of the furnace. Then they are disconnected and the substrate plate is released. The releasing time of the plate is about 1 minute due to the application of special yokes mentioned above. After release, the slide is cooled in air (few minutes) and then washed with running deionized water.

Figure 2 presents crucibles applied at the stand. The holes visible in the upper and bottom parts of the crucibles are used to install the clamping yoke. Each time before

Fig. 2. Crucibles.

the crucibles are used, their front surface is subjected to short grinding process on abrasive dust to make it smooth. Then the crucibles are chemically washed to remove fat. After that the front surfaces are coated with a thin layer of silicone, and then an appropriately prepared glass slide is placed between them. To ensure that the silicone gets hard, the said process is carried out a few hours before the crucibles are placed into the furnace.

3. Technological processes

As a base for the production of waveguide, we applied commercially available soda -lime glass in the form of object plates used for microscopy. This kind of glass contains a relatively high amount of sodium (see Tab. 1). Waveguide structures obtained in this glass are characterized by a relatively low attenuation. Its refractive index for the wavelength $\lambda = 677$ nm applied in the investigation is $n_{677} = 1.5111$. The Ag^+ ions were used as dopant introduced to glass (dopant source – pure $AgNO_3$). The applied process temperatures were about 300°C.

T a b l e 1. Composition of the soda-lime glass substrate.

Compounds [wt.%]						
SiO_2	Al_2O_3	Na_2O	K_2O	CaO	MgO	Others
75	0.6	12.2	0.2	7.4	3.9	0.7

Table 2 presents the parameters of four thermal diffusion processes realized at the same temperature for various duration times which did not exceed 2.5 h.

Because the amount of dopant introduced to the glass during the electrodiffusion process is reported by an electric charge passing through the glass substrate – for each process, the dependence of current on duration time of the process was recorded.

T a b l e 2. Thermal diffusion processes.

No. of sample	Temperature of the process [°C]	Duration of the process [hours]
1	300±1	1.0
2	300±1	1.5
3	300±1	2.0
4	300±1	2.5

Table 3 presents the parameters of electrodiffusion processes with a fixed direction of the external electric field polarization. The duration time of each of these processes was the same, that is, 1 h. The table also presents the total value of electric charge calculated on the basis of the passing current.

As was already mentioned, in the electrodiffusion processes during which the direction of the external electric field polarization is changed, the introduction of

T a b l e 3. Electrodiffusion processes with the fixed direction of electric field polarization.

No. of sample	Temperature of the process [°C]	Duration of the process [hours]	Intensity of electric field [V/mm]	Electric charge [C]
1	300±1	1.0	4.5	1.02
2	299±1	1.0	9.1	2.29
3	299±1	1.0	18.2	4.99
4	300±1	1.0	27.3	7.38

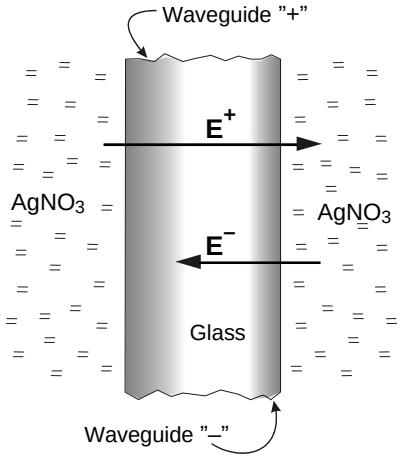

Fig. 3. Simultaneous formation of two waveguides in the electrodiffusion process with forward $\mathbf{E}^+$ and reverse $\mathbf{E}^-$ electric field polarization.

dopant to glass is taking place on both sides of the substrate. As a result, the waveguide structures are formed on both sides of the substrate plate. In order to make a distinction between these structures the following marking was assumed: waveguide *A* was being produced on the side of substrate where the initial polarization of electric field (forward field) was supporting the penetration of dopant into the substrate, waveguide *B* was being produced on the opposite side of the substrate (see Fig. 3). Figure 3 presents also conventionally assumed states of positive (forward) and negative (reverse) polarization. The parameters of the technological processes carried out are presented in Tab. 4. The duration time of each process given in the table consists of two values corresponding respectively to the positive polarization and the negative one. For each substrate we have here two waveguides *A* and *B*. The table presents also the total electric charge of dopant ions which entered the glass substrate from each side.

4. Experimental results

The measurements of propagation constants of modes of the planar waveguides produced were effected by the determination of synchronic angles, using a prism

T a b l e 4. Electrodiffusion processes with the single cycle forward-reverse field application.

No. of sample	Waveguide	Temperature of the process [°C]	Duration of the process [min]	Polarization and intensity of electric field [V/mm]	Electric charge [C]
1	*A*	272±1	30/30	+18.2/–9.1	1.130
	B		30/30	–18.2/+9.1	0.572
2	*A*	298±1	75/15	+18.2/–9.1	5.680
	B		15/75	–18.2/+9.1	0.572
3	*A*	298±1	60/30	+18.2/–9.1	4.755
	B		30/60	–18.2/+9.1	1.172
4	*A*	298±1	30/60	+18.2/–9.1	3.280
	B		60/30	–18.2/+9.1	2.951
5	*A*	298±1	45/45	+18.2/–13.6	3.636
	B		45/45	–18.2/+13.6	0.144
6	*A*	298±1	45/45	+18.2/–9.1	3.719
	B		45/45	–18.2/+9.1	1.774
7	*A*	298±1	45/45	+4.5/–18.2	0.908
	B		45/45	–4.5/+18.2	4.164
8	*A*	299±1	30/30	+18.2/–9.1	2.554
	B		30/30	–18.2/+9.1	1.252
9	*A*	299±1	45/45	+18.2/–18.2	4.654
	B		45/45	–18.2/+18.2	4.777
10	*A*	299±1	50/40	+18.2/–9.1	3.688
	B		40/50	–18.2/+9.1	1.803
11	*A*	300±1	45/45	+13.6/–18.2	2.965
	B		45/45	–13.6/+18.2	4.240
12	*A*	301±1	45/45	+9.1/–18.2	1.628
	B		45/45	–9.1/+18.2	3.791

coupler. The measurements were carried out for both polarization TE and TM, for the wavelength $\lambda = 677$ nm. The refractive index profiles of the waveguides produced were reconstructed using a mode equation [12]. The results of measurements have uncertainty of $\Delta N_{\text{eff}} = 0.0003$.

In the waveguide structures produced, the phenomenon of birefringence was not reported – the refractive index profiles for TE and TM polarization were not considerably different within the limits of measurement error. Therefore, in the further part, when presenting the diagrams which illustrate the shapes of refractive index profiles, we present the reconstructions obtained only for the TE polarization. Since the reconstruction of refractive profile for the said method is the more reliable the higher the number of modes is, therefore adequately high values of time were selected for the realization of technological processes in order to bring about a relatively deep doping of glass.

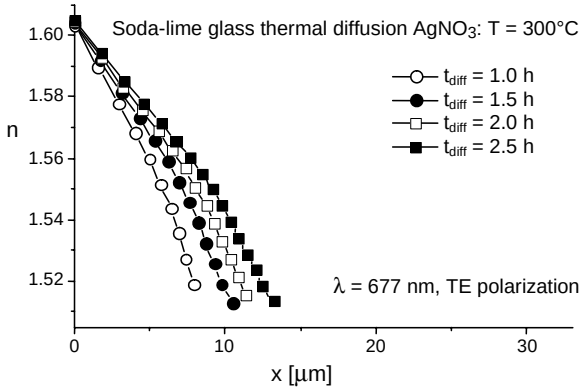

Fig. 4. Refractive index profiles of waveguides produced by pure thermal diffusion according to Tab. 2.

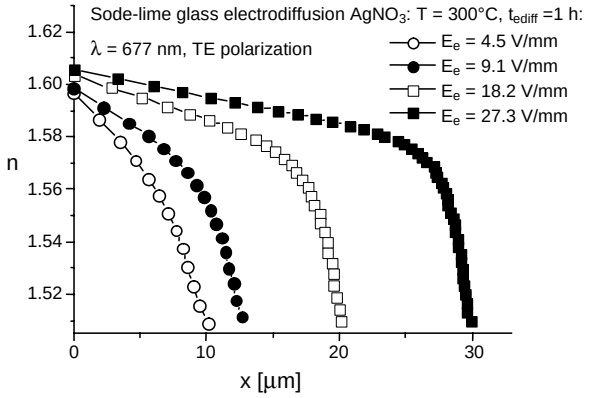

Fig. 5. Refractive index profiles of waveguides produced by electrodiffusion with fixed forward polarization (according to Tab. 3).

Figure 4 presents refractive index profiles of waveguides produced in purely thermal diffusion processes according to Tab. 2. Figure 5 presents the refractive index profiles produced in electrodiffusion processes with the fixed direction of the electric field polarization. The duration time of all the processes (according to Tab. 3) was the same here, *i.e.*, 1 h. We can observe that there is an obvious dependence involving the influence of the intensity of electric field on the depth of the refractive index profile obtained. However, in this case, the forms of refractive index profiles of the waveguides are quite similar.

Relevant differences in the shape of refractive index profiles can be observed when we change the direction of electric field polarization during the process. Let us consider the situation where the direction of the applied electric field polarization is changed only once (one cycle forward-reverse electric field application). During such a process, with the positive (forward) polarization (Fig. 3) dopant ions entering the glass substrate form a waveguide *A*. On the other side of the substrate, despite its contact with dopant

source (liquid $AgNO_3$) a waveguide is not produced since glass ions, due to the current passing through the glass substrate, go to the liquid phase. After the change of direction of polarization the situation is reverse. Now, the current is passing through the glass substrate in the opposite direction. A waveguide *B* is beginning to form on the other side of glass whereas the reverse stream of ions of the dopant introduced earlier to glass together with glass ions is changing the distribution of the dopant with the positive polarization. In consequence, the refractive index profile of the waveguide *A* changes. As regards to the process with only one change of direction of electric field polarization there are great potentials to influence the final form of the refractive index profile of the waveguide *A*. We can change here both the time relationship involving the duration of positive or negative polarization and the values of electric field intensity for forward and reverse field (see Fig. 3). When we carry out electrodiffusion processes with multiple cycles forward-reverse field application – we have increased number of

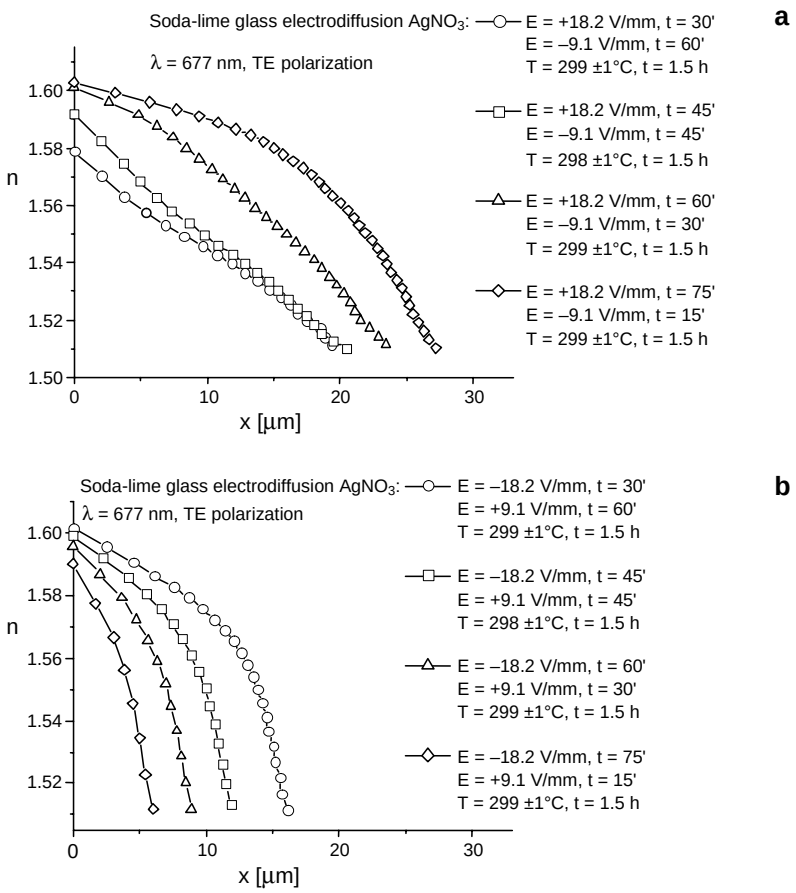

Fig. 6. Comparison of refractive index profiles of waveguides produced in electrodiffusion processes with settled values of fields: E^+ = 18.2 V/mm, $E–$ = –9.1 V/mm and different reports of duration of polarization "+" and "–". The waveguides produced on the first side of the substrate (**a**) and the second one (**b**).

parameters (direction of polarization, duration time of polarization, field intensity) which determine the final character of refractive index profile both on one side and on the other side of glass substrate.

Figure 6 present refractive index profiles of waveguides produced in electrodiffusion processes in which there are fixed values of field intensity for the polarization "+" and "–" (see Fig. 3). The ratio involving the duration time of polarization "+" and "–" was changing here, with the total duration time of the process t = 1.5 h being unchanged. Waveguides of the type *A* and *B* were produced on the opposite sides of the substrate plate. The same centered symbols on both diagrams (**a** and **b**) denote the same glass substrates in which respective waveguides were produced.

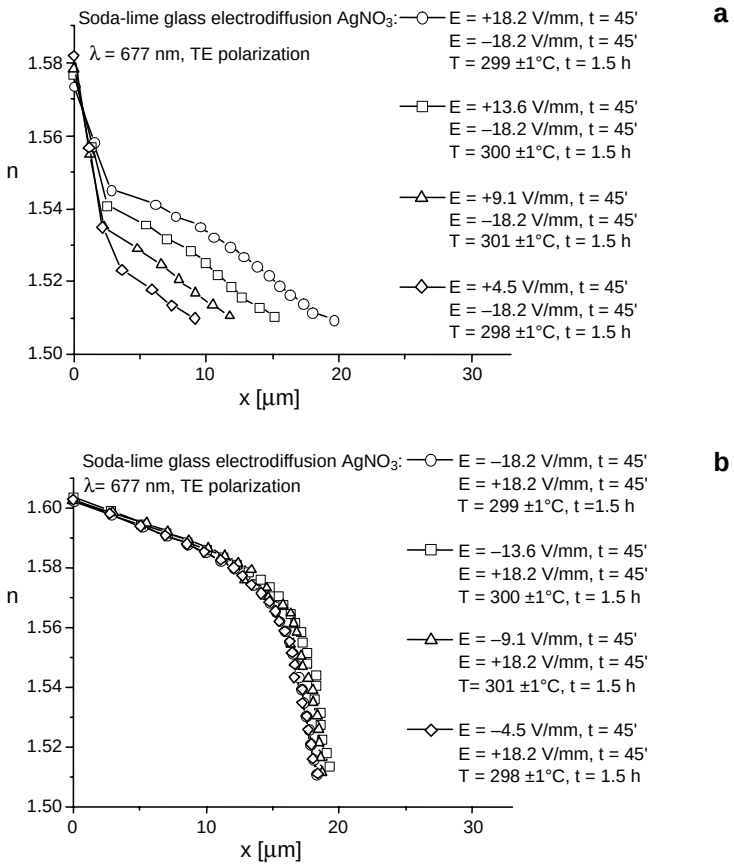

Fig. 7. Comparison of refractive index profiles of waveguides produced in electrodiffusion processes with settled time of duration of polarization t^+ = 45 min and t^- = 45 min and different mutual reports of intensity of electric field for polarization "+" and "–". The waveguides produced on the first side of the substrate (**a**) and the second one (**b**).

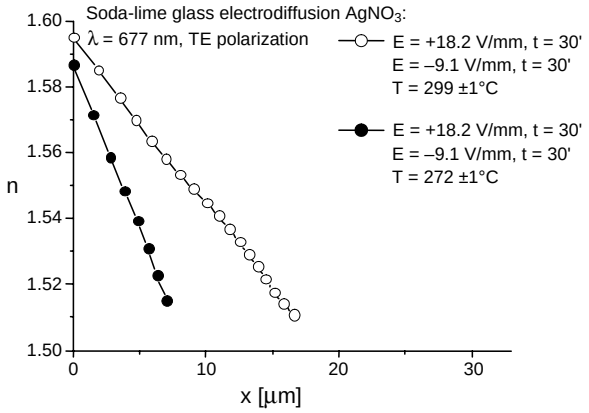

Fig. 8. Produced refractive index profiles of waveguides with the form approximate to linear.

In Figure 7, there are compared refractive index profiles for waveguides produced in the processes for which the duration time of each polarization was divided (the total duration time of the process t = 1.5 h). We changed the values of electric field intensity for both directions of polarization. As before, waveguides of the type *A* and *B* were produced here on the opposite sides of substrate plate. The same centered symbols on both diagrams (**a** and **b**) denote the same glass substrates in which respective waveguides were produced.

As was mentioned before, through an appropriate selection of duration time for a particular direction of polarization, and the value of electric field intensity we can intentionally obtain a desired form of refractive index profile of the waveguide.

From the results presented in Fig. 6**a** it follows that it is possible to produce the form of refractive index profile approximate to linear one. The intensity of electric field in direction "+" is here twice that of the "–" one. The time of duration of both directions of polarization is here the same. On this basis, two attempts at producing a waveguide with about a linear form of refractive index profile were realized.

Figure 8 presents refractive index profiles of the shapes similar to linear one, obtained in electrodiffusion processes in which duration time of polarization "+" and "–" was the same (t = 30 min), and the values of field intensity were E = 18.2 V/mm and E = –9.1 V/mm, respectively. The temperatures of both processes were 299°C and 272°C, respectively. The refractive index profiles have different depth, which is the result of the dependence of electric mobility of ions on temperature. In the case of the waveguide produced at a lower temperature, the influence of a diffusive component, as compared to the electric drift – on the final form of refractive index profile shape – is much smaller.

Figure 9 present refractive index profiles of waveguides produced on both sides of glass substrate in the electrodiffusion process with multiple cycles forward-reverse

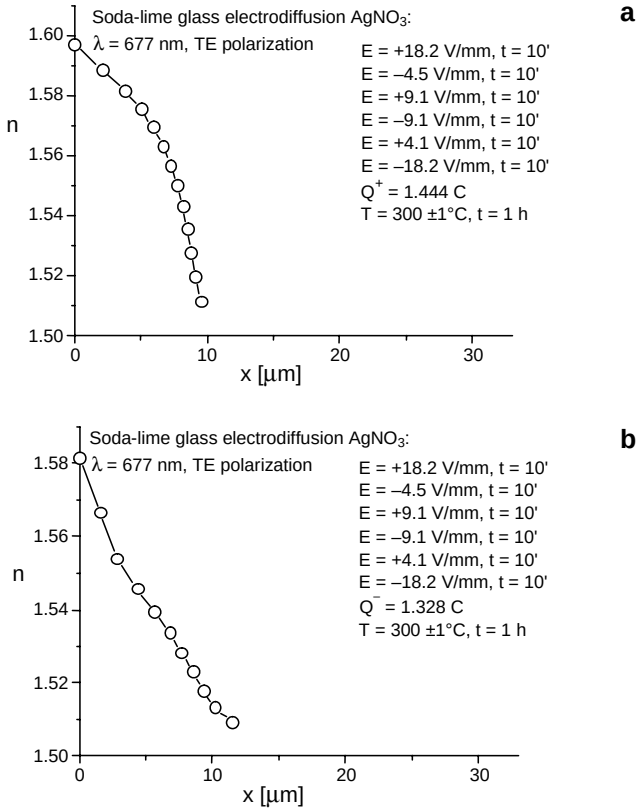

Fig. 9. Refractive index profiles of waveguides produced in process with multiple cycles forward-reverse field application. The waveguide produced on the first side of the substrate (**a**) and the second one (**b**).

field application. The total duration time of the process was 1 h. Duration times of each direction of the polarization were the same here, *i.e.*, 10 min. In this figure, there are also given the total values of electric charge which passed in one and in the other direction through the glass substrate.

5. Relationship between the change of refractive index of the waveguide and electric charge in electrodiffusion processes

In the electrodiffusion process the value of charge Q_τ which has passed through the glass is a quantity measurable based on the current relation $i(t)$:

$$Q_\tau = \int_0^\tau i(t)\mathrm{d}t, \tag{1}$$

and the refractive index profile $n(x)$ of planar waveguide is defined by the following relation [1] (see Fig. 10):

$$n(x) = n_s + \Delta n\, u(x) \tag{2}$$

where: Δn – maksimum change of refractive index on the surface of waveguide, $u(x)$ – normalized concentration of admixture introduced into glass. Since $u(x) = c(x)/c_0$, where c_0 (m^{-3}) is the equilibrium concentration of mobile components of glass (concentration of b ions in virgin glass), therefore Eq. (2) can be written in the following form:

$$n(x) = n_s + \Delta n \frac{c(x)}{c_0}. \tag{3}$$

Introducing the function:

$$\delta n(x) = n(x) - n_s \tag{4}$$

we obtain from Eq. (3)

$$c(x) = \delta n(x) \frac{c_0}{\Delta n} \quad [m^{-3}]. \tag{5}$$

Equation (5) presents the distribution of concentration of the dopant introduced to glass expressed by means of the parameters of refractive index profile and equilibrium concentration c_0.

Integrating the expression (5) over the whole volume of glass V, we obtain the summary number of ions N_τ of the dopant introduced to glass in the electrodiffusion process in time τ

$$N_\tau = \int_V c(x)\mathrm{d}V = \frac{c_0 S}{\Delta n} \int_0^z \delta n(x)\mathrm{d}x. \tag{6}$$

In the above equation S stands for transverse section of glass (the active section of exchange) in which dopant source gets into contact with glass, z is the depth of refactive index profile (see Fig. 10).

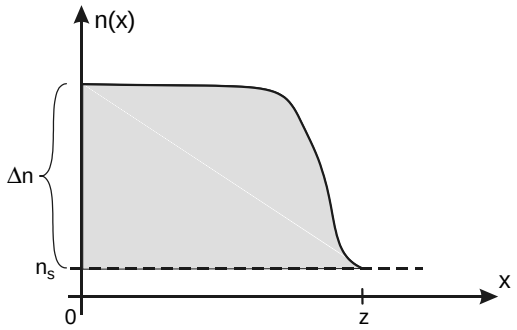

Fig. 10. Parameters of refractive index profile of wavegude produced by electrodiffusion.

Based on Eq. (1) the total charge which has passed through the glass, we can determine the number of dopant ions which were introduced to glass in time τ

$$N_\tau = \frac{1}{we}\int_0^\tau i(t)\,\mathrm{d}\tau = \frac{Q_\tau}{we} \tag{7}$$

where e stands for elementary charge, and w – for valency of ions.

Comparing (6) and (7) we obtain:

$$\int_0^z \delta n(x)\,\mathrm{d}x = \frac{\Delta n}{ewSc_0} Q_\tau \quad [\mathrm{m}]. \tag{8}$$

Table 5 presents the calculation results of the product of equilibrium concentration and active cross-section of the exchange Sc_0 based on Eq. (8) for several electrodiffusion processes carried out in the base from soda-lime glass, using pure $AgNO_3$ as the dopant source of ions Ag^+ ($w = 1$). In this table there are also present the relation $\Delta n(Q_\tau)$ calculated on the basis of the refractive index profiles and Eq. (1). The above considerations show that it is possible to determine equilibrium concentration in substrate glass.

Yet, the determination of active cross-section through which the passage of the charge is taking place bears some uncertainty effected by gradual trickling of melted salt around the edges of the crucibles where the sealing was applied. Another disadvantage is the fact that the electric field is not homogeneous along the edges of glass substrate (edges of the crucibles). This heterogeneity brings about a situation where the dopant in this area is introduced meaningfully deeper into the glass than in

T a b l e 5. Parameters of electrodiffusion processes.

Q_τ [C]	$\int_0^z \delta n(x)\mathrm{d}x$ [m]	Δn	E [V/mm]	T [°C]	τ [min]	Sc_0 [m^{-1}]	$c_0 \pm \Delta c_0$ [m^{-3}]
0.572	0.2967×10^{-6}	0.0789	9.1	299±1	15	9.49×10^{23}	$(2.6\pm0.5)\times10^{27}$
0.957	6.2945×10^{-6}	0.0854	4.5	300±1	60	8.12×10^{22}	$(2.3\pm0.4)\times10^{26}$
1.172	0.5064×10^{-6}	0.0846	9.1	299±1	30	1.22×10^{24}	$(3.4\pm0.6)\times10^{27}$
1.774	0.7264×10^{-6}	0.0879	9.1	298±1	45	1.34×10^{24}	$(3.7\pm0.7)\times10^{27}$
2.035	8.6501×10^{-6}	0.0878	9.1	299±1	60	1.29×10^{23}	$(3.6\pm0.7)\times10^{26}$
2.951	1.0289×10^{-6}	0.0902	9.1	299±1	60	1.61×10^{24}	$(4.5\pm0.8)\times10^{27}$
3.791	1.3337×10^{-6}	0.0912	18.2	301±1	45	1.62×10^{24}	$(4.5\pm0.8)\times10^{27}$
4.164	1.2699×10^{-6}	0.0916	18.2	298±1	45	1.87×10^{24}	$(5.2\pm1.0)\times10^{27}$
4.240	1.3527×10^{-6}	0.0925	18.2	300±1	45	1.81×10^{24}	$(5.0\pm0.9)\times10^{27}$
4.777	1.2706×10^{-6}	0.0912	18.2	299±1	45	2.14×10^{24}	$(5.9\pm1.0)\times10^{27}$
4.996	15.3553×10^{-6}	0.0952	18.2	299±1	60	1.94×10^{23}	$(5.4\pm1.0)\times10^{26}$
7.377	23.9859×10^{-6}	0.0955	27.3	300±1	60	1.83×10^{23}	$(5.1\pm1.0)\times10^{26}$

the area where the electric field is homogenous. The values of integrals in the second column of Tab. 5 are estimated with the assumption that the shape of refractive index profile on the whole surface of the active cross-section of glass is the same. With such reservations we can attempt to estimate the equilibrium concentration in glass. Assuming that the active cross-section of the crucible $S = (3.6 \pm 0.7)\times10^{-4}$ [m^2] is the same for all processes presented in Tab. 5, we obtain mean value $c_0 \approx 3\times10^{27}$ [m^{-3}].

Based on the composition of soda-lime glass presented in Tab. 1 we can determine its mean molar mass $M_{\text{glass}} = 60$ [g/mol]. The density of this glass is $\rho = 2.59$ [g/cm^3]. This, in turn, allows us to estimate the mean concentration of glass components using the following relation:

$$c_s = \frac{\rho N_A}{M_{\text{glass}}} = 2.6\times10^{28} \quad [\text{m}^{-3}] \tag{9}$$

where N_A stands for Avogadro's number. Now, the estimated value of equilibrium concentration of mobile glass components, with respect to mean concentration of all components of glass, is $c_0/c_s = 0.11$. This value illustrates well the composition of glass (Table 1) in which 12% is made up by Na_2O contributing to its composition ions Na^+ which have one of the lowest activation energies in glass network [13].

Based on the data given in Tab. 5, in Fig.11 we present the relationship between the maximum value of the change of refractive index on the surface of waveguide Δn and the value of electric charge Q_τ which passed during the process of its production. The matched curve has the following equation:

$$\Delta n(Q_\tau) = a\left[1 - b\exp\left(-\frac{Q_\tau}{c}\right)\right]. \tag{10}$$

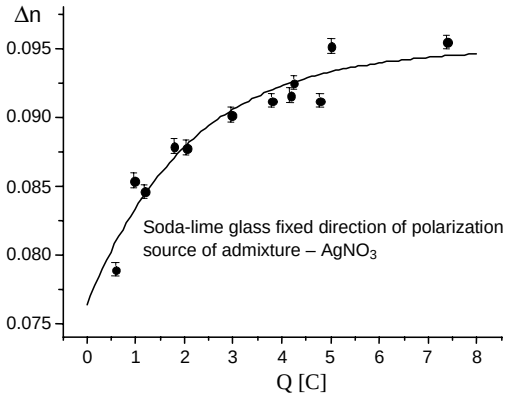

Fig. 11. Dependence of maximum change coefficient of refraction on the surface of waveguide *vs.* electric charge passed in the process of electrodiffusion.

The matching parameters obtained are as follows: $a = 0.095 \pm 0.002$, $b = 0.197 \pm 0.020$, $c = 2.085 \pm 0.689$ [C]. This relationship refers to the waveguides produced in the processes with fixed direction of electric field polarization, and with the same active cross-section of the crucible $S = (3.6 \pm 0.7) \times 10^{-4}$ [m^2].

6. Conclusions

The work presents the results of investigation on refractive index profiles of planar waveguides produced in electrodiffusion processes in soda-lime glass.

An original technological stand was presented whose principle of operation allows the duration time of technological process to be precisely controlled. Pure silver nitrate $AgNO_3$ was applied as dopant source. The temperatures of processes ranged from 271 to 301°C. The phenomenon of birefringence was not reported to occur in all the waveguides produced. We realized electrodiffusion processes with both fixed and changed direction of the electric field polarization during the process.

It was demonstrated that electrodiffusion processes with the only one cycle forward-reverse field application offer potentials to produce planar waveguide structures in glass bases, whose refractive index profiles can be shaped within a wide range through an appropriate selection of electric field polarization and duration time of the process. We also present the experimentally obtained refractive index profiles of the run close to linear one.

For electrodiffusion processes with the fixed direction of polarization it is possible to estimate equilibrium concentration of mobile ions of glass.

For a given system glass-dopant, electrodiffusion processes with the alternating electric field offer new potential to form refractive index profiles with parameters defined in advance. Such a wide range involving the formation of refractive index profiles cannot be obtained either in single or multiple processes of thermal diffusion. Further continuation of the research is planned on the application of such processes for the production of strip waveguide structures.

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