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Present state and perspectives involving application of ion exchange in glass

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This paper presents recent developments in investigations of glass integrated optical circuit. Components are realised by the waveguide technologies: single ion exchange, creating of buried strip waveguides, double ion exchange, and doped glass strip waveguides. Moreover, double refraction of glass planar waveguides, equipment and elements on glass planar waveguides and multimode interference structures in the technology of elements of integrated optics and plasmon interaction are illustrated.

Keywords: integrated optics, ion exchange in glass.

1. Introduction

Intensive development of optoelectronics, and in particular waveguide optoelectronics and waveguide technology, is inspiring the development of integrated optoelectronics. Over the last several dozen years people have become aware of application potentials offered by integrated optical systems that can change the size of classical optical systems to planar optical systems measuring a few centimetres. The 1970s gave rise to the production of planar optical processors performing definite functions involving the transformation of signals. The said facilities perform functions that have not been so far realised in the field of volumetric optics, e.g., planar optical heterodyne receivers. The combination of planar structures with fibre waveguides results in creation of hybrid systems. Fibre waveguides function as transmission lines, and the units of integrated optics perform definite functions of signals transformation.

The elements of integrated optics can be used in such spheres of waveguide optics as:

- local networks, computer networks, networks for control or automation systems,
- integrated telecommunications systems (optical T-junctions, electroptical switches, multi- and demultiplexers, etc.),
- sensors and waveguide interferometers,
- optical logic elements.

From among a few technologies applied currently in integrated optoelectronics, the technology of ion exchange in glass seems to be the most expansive. Technological processes based on ion exchange in glass used for the production of such elements of integrated optics as: couplers, T-junctions, double waveguide multi- and demultiplexers, sensors became developed enough to meet the requirements of large-scale production.

2. Ion exchange in glass

2.1. Single ion exchange

The principal property of glass, which is determining its application as a base element in gradient planar optics, is the possibility to carry out ion exchange processes in this glass. Guiding out of glass a certain number of modifier ions and replacing them with the ions of other metals (in the following part referred to as impurity) makes it possible to create local changes of optical properties of glass in its surface area. Such a process can be effected after the creation of glassy structure, after melting it and giving it a definite form (plates, bars, profiles, etc.) by appropriate mechanical working.

The impurity ions introduced to glass take over the places in the glass structure left by modifier ions. Therefore after the exchange of these ions the structure of glass is left unchanged. The changes involve optical properties of glass due to different electrical polarisabilities of the exchanged ions, difference in their size (ionic radii) and created mechanical stresses. By expressing refractive index of glass by means of the refraction of its components [1]

$$n = 1 + \frac{R_0}{V_0}, \tag{1}$$

where R_0 is the molar refraction of oxygen atoms (cm^3/mole), V_0 is the molar volume of oxygen atoms (cm^3/mole). We can express the change δn of refractive index of glass effected by the replacement of some part χ of glass ions by impurity ions by the following relation [1]

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$$\delta n = \frac{\chi}{V_0}\left(\Delta R - R_0\frac{\Delta V}{V_0}\right), \tag{2}$$

ΔR and ΔV stand here for the changes of values R_0 and V_0 effected by the exchange of ions. The first component of Eq. (2) is the factor contributing to the change of polarisability. The second element is the result of the change of glass volume caused by the difference in ionic radii. Table 1, after Ref. 2, presents the values of electrical polarisability and ionic radii of impurities most often used in ion exchange processes compared with sodium treated as the main component which modifies glass. Basing on Eq. (2), we can treat the global change of refractive index as a linear function of concentration of the introduced impurity c(x, y, z) [1]

$$\delta n(x, y, z) \sim c(x, y, z). \tag{3}$$

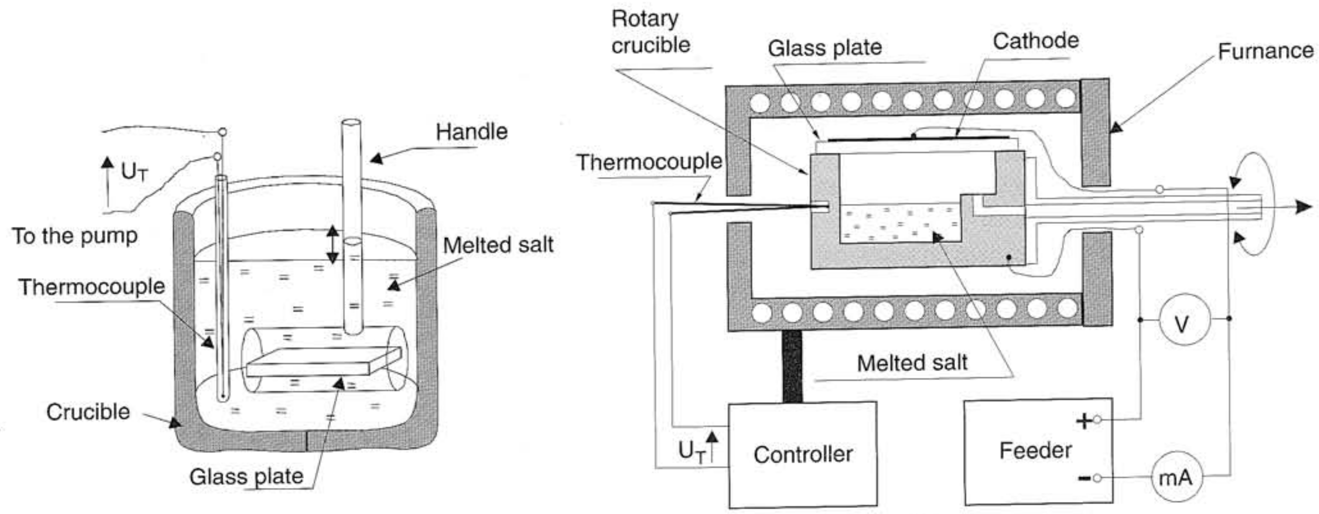
Table 1. Ions of the modifiers (after Ref. 2)

Ion	Electrical polarizability ($\times 10^{-30}$ m^3)	Ionic radius ($\times 10^{-10}$ m)
Li^+	0.03	0.68
Na^+	0.43	0.95
Ag^+	2.40	1.26
K^+	1.33	1.33
Tl^+	5.20	1.49
Rb^+	1.98	1.49
Cs^+	3.34	1.65

The above assumption constitutes a basis for the modelling of changes of refractive index obtained by the processes of diffusive and electrodiffusive introduction of impurity to glass. Technological processes which effect ion exchange in glass are most often carried out with the use of liquid sources of impurity (melted nitrates: silver and potassium ones). Initial introduction of impurity to glass can be carried out in the process of purely thermal diffusion, as well as in the presence of electrical field (electrodiffusion). The initial distribution of impurity in glass and resulting from it distribution of refractive index can be afterwards modified in the secondary processes (diffusion, electrodiffusion, heating). By the application of sources of ion impurity, lowering the refractive index in secondary processes, it is possible to produce the structures of so-called buried waveguides in which the maximum value of refractive index is moved under the surface of glass base. Figure 1 presents exemplary diagrams of technological stands for the realisation of diffusion or electrodiffusion processes with application of liquid sources of impurity.

The designing process of waveguide structures with the use of ion exchange technique in glass is based on the adoption of mathematical model which enables the description of particular technological processes. Parameters determining the kinetics of ion exchange are defined for a given system glass-impurity by the measurement of refractive profile of the waveguide made in a definite technological process and by matching the obtained measurement points with the solution of equation which describes a given process basing on the accepted mathematical model. The geometry of the system was accepted as in Fig. 2. After introduction of the impurity A, two streams of ions effected by the gradients of their concentration will occur in the glass area

$$\begin{aligned}\vec{\Phi}_A &= -D_A\nabla c_A + \mu_A c_A\vec{E}_o \quad (m^{-2}s^{-1}).\\ \vec{\Phi}_B &= -D_B\nabla c_B + \mu_B c_B\vec{E}_o \quad (m^{-2}s^{-1})\end{aligned} \tag{4}$$



(a) (b)

Fig. 1. Section of crucible with hydraulic mixer for the realisation of thermal diffusion processes (a), section of furnace allowing carrying out electrodiffusion processes with the application of liquid impurity source (b).

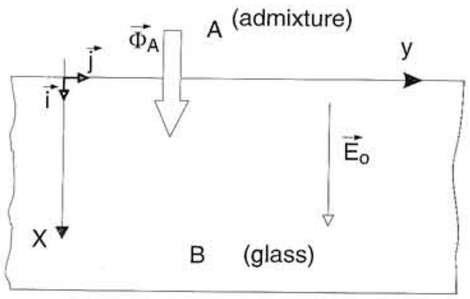


Fig. 2. Geometry of the system.

In the above equations

$$\vec{E}_o = \vec{E}_e + \vec{E}_d,$$

where $\vec{E}_o$ is the local electric field (Vm^{-1}), $\vec{E}_e$ is the external electric field (Vm^{-1}), $\vec{E}_d$ is the diffusive electric field resulting from the difference in mobility of the exchanged ions (Vm^{-1}).

Due to possible difference of diffusion constants D_A and D_B of both ion types, a so-called diffusive potential occurs in the glass, which results from the difference in their mobility. The electric field E_d connected with the said potential is a factor which couples the movement of both streams (slower ions will be accelerated, and the faster ones will be slowed down by this field). The external, additional electric field E_e presented in Fig. 2, allows to generalise the investigated exchange process (electrodiffusion). The equilibrium concentration: $c_0 = c_A + c_B$, ($c_0 = c_B$ in glass before the exchange) and normalised concentration of ions are introduced: $u = c_A/c_0$ and $w = c_B/c_0$ satisfying the condition $u + w = 1$. For diffusion constants of both types of ions, the dependence on normalised concentrations is assumed as follows [3]:

$$\begin{aligned} D_A(u) &= D_{0A}\exp(Au), \\ D_B(w) &= D_{0B}\exp(Bw), \\ D_{0i} &= D_{0i}^{*}\exp\left(-\frac{\Delta Q_i}{RT}\right) \qquad (i = A, B) \end{aligned} \tag{5}$$

In the above equation ΔQ_i stands for activation energy of the i-th element ($Jmole^{-1}$], R is the stands for universal gas constant ($JK^{-1}mole^{-1}$].

Taking into consideration Eq. (5), from Eqs. (4) we can obtain the following equation [4]:

$$\begin{aligned} \frac{\delta u}{\delta t} = \frac{D_A}{1-\alpha u}\left[\Delta u + \frac{\alpha}{1-\alpha u}(\nabla u)^2 - \frac{e}{HkT}\cdot\frac{1}{1-\alpha u}\nabla u\vec{E}_e\right] + \\ \frac{1-u}{(1-\alpha u)^2}\left[\nabla u - \frac{e}{HkT}u\vec{E}_e\right]\nabla D_A + \\ \frac{u(1-\alpha)^2}{(1-\alpha u)^2}\left[\nabla u - \frac{e}{HkT}u\bar{E}_e\right]\nabla D_E \end{aligned} \quad . \tag{6}$$

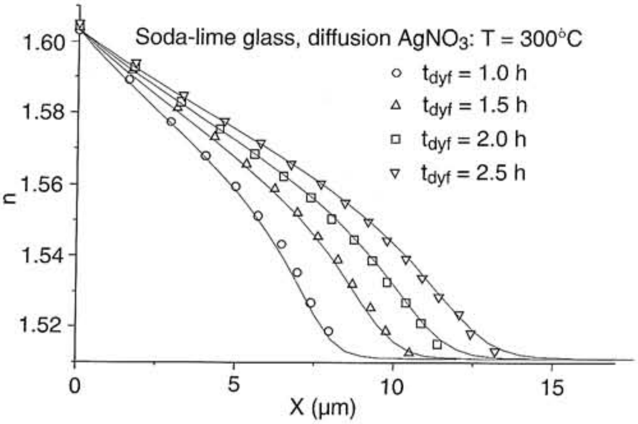


Fig. 3. Refractive profiles of planar waveguides (measurement points) obtained in sodium-calcium glass in ion exchange processes $Ag^+ \leftrightarrow Na^+$ – diffusion with the application of melted (T = 300°C) $AgNO_3$ as impurity source, different duration times of the processes. Full lines stand here for the solutions of equation (6) obtained for the parameters D_{0A} = 1.63 μm²/h, D_{0B} = 19.44 μm²/h, A = 3.75, B = 0.165.

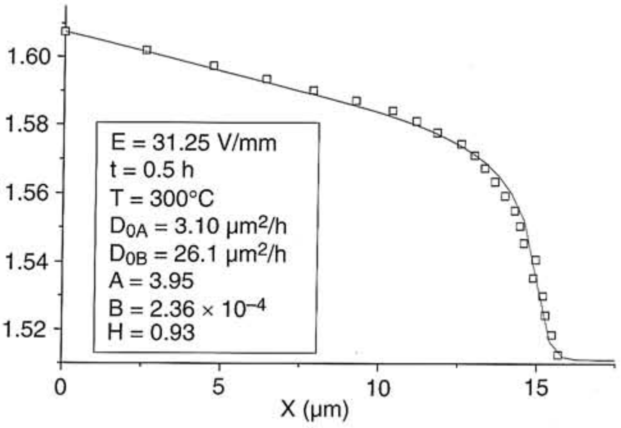


Fig. 4. Solution of Eq. (6) (full line) describing electrodiffusion process matched to measurement points defining refractive profile. Planar waveguide made in sodium-calcium glass through ion exchange $Ag^+ \leftrightarrow Na^+$ in the presence of electric field (E = 31.25 V/mm), with the application of melted (T = 300°C) $AgNO_3$ as impurity source.

The above equation together with respective initial and boundary conditions permits to model respective technological processes that are used for the production of both planar and strip waveguide structures. Figures 3 and 4 present exemplary modelling results of thermal diffusion and electrodiffusion basing on Eq. (6). With the application of these processes the structures of planar waveguides in sodium-calcium glass were made, where the melted silver nitrate was used as the liquid impurity source of ions Ag^+. By matching the solutions of the equation (6), which is describing a respective process, with the points of measured refractive profile of the waveguide, respective values of parameters D_{0A}, D_{0B}, A and B were determined from Eq. (5).

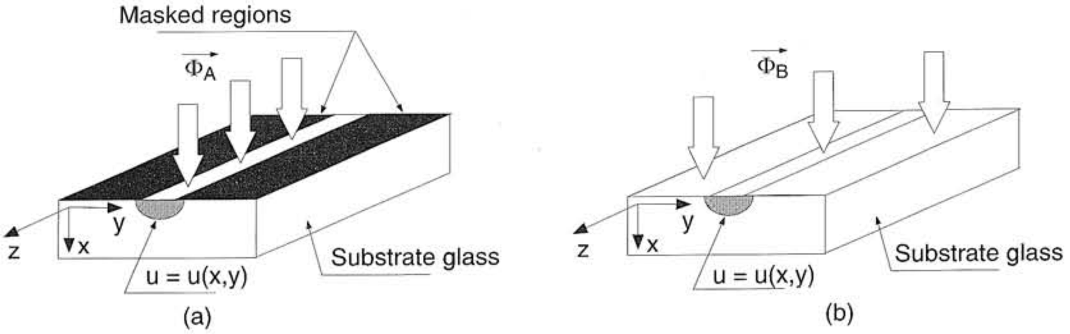


Fig. 5. Schematic presentation of processes involving the production of strip buried waveguide: (a) generation of the initial distribution of refractive index, (b) lowering the value of refractive index on the surface side of base glass.

2.2. Production of buried strip waveguides

Buried waveguide structures are characterised by the position of maximum value of refractive index shifted under the surface of base glass. Waveguides of that type (planar, strip ones) are usually made in successive technological process whereof the first (thermal diffusion, electrodiffusion) effects the initial distribution of refractive index in glass. Refractive profile always has here maximum value located on the surface of glass. The role of the next process (processes) is to shift this maximum value under the surface of glass. Such an effect is obtained by the introduction of ions to glass, which lower the value of refractive index in the area where the impurity has been already introduced. At this stage the processes of thermal diffusion or electrodiffusion can be also applied. When we know the parameters characterising the kinetics of secondary ion exchange, we can form the buried refractive profile by respective selection of technological parameters of the carried out processes. By the application of liquid sources of impurity ions, the structures of buried strip waveguides are produced with the use of masking layers (thin metallic layers, generally Al) deposited on the surface of base glass. In such layers, using photolithographic processes, the definite topology of waveguide structure is formed.

In the initial process (diffusion, electrodiffusion), impurity ions which form the initial waveguide structure are introduced into the unmasked areas of glass (Fig. 5a). The secondary process, consisting in the introduction of impurity ions lowering the refractive index, is carried out over the whole glass surface after the masking layer has been removed (Fig. 5b). In the description of the above processes with the application of mathematical model presented in Chapter 2.1, respective initial and boundary conditions must be introduced to Eq. (6). The initial distribution taking place in glass of the impurity obtained after the initial process is the initial condition for burying process. Exemplary numerical solutions of Eq. (6) in this case are presented in Fig. 6.

Figure 7 presents the measured refractive profile of the buried planar waveguide in sodium-calcium glass in the processes of initial diffusion of ions Ag^+ and secondary diffusion of ions Na^+ which result in the lowering of the change (δn) of refractive index on glass surface.

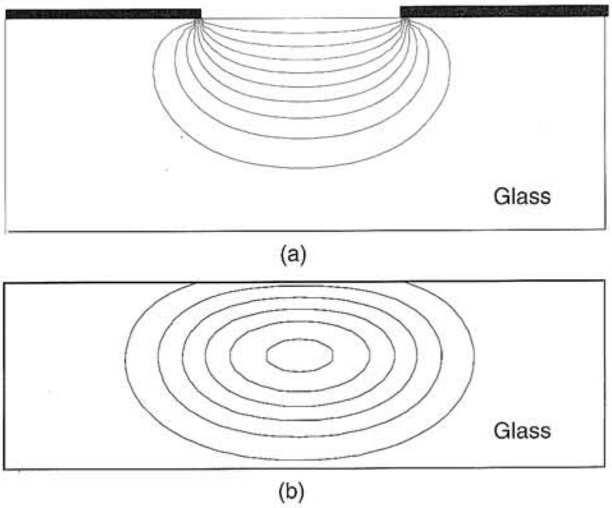


Fig. 6. Solution of Eq. (6) while modeling the refractive profile of strip waveguide obtained in the process of introductory diffusion with the use of metallic mask (a), and subjected to burying process over the whole surface of glass after the removal of mask (b).

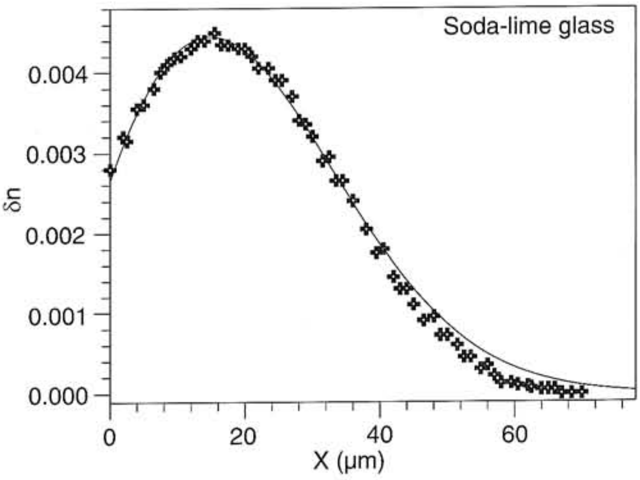


Fig. 7. Matching the solution of the equation of secondary diffusion with the profile of planar waveguide made in sodium-calcium glass in the following processes: introductory diffusion of ions Ag^+: T = 290°C (563 K), t = 2h, + secondary diffusion of ions Na^+: T = 370°C (643 K), t = 8 h.

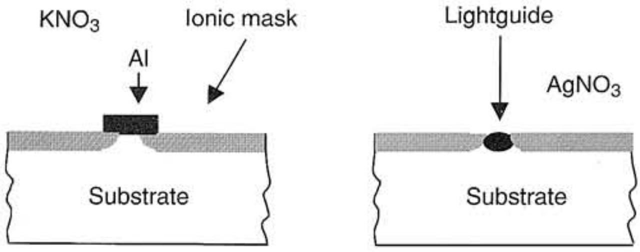


Fig. 8. Production process of strip waveguide using the technique of silver ions exchange with the use of ion mask (after Ref. 15).

2.3. Double ion exchange

The slowness of ions K$^+$ is used to block the diffusion of Ag$^+$ when producing, e.g., strip waveguides using the method of double ion exchange. At the first stage the plate masked by the strips of Al layer is immersed in the bath KNO$_3$, ions K$^+$ penetrate the glass into uncovered areas of the plate. After this exchange, the mask is removed and the plate is subjected to the exchange process in AgNO$_3$ at lower temperature and over shorter time that at the first stage. In the areas where ions K$^+$ have already entered, the penetration of ions Ag$^+$ is blocked; due to low mobility of ions K$^+$ the exchange mechanism can not take place. Silver ions can enter the glass only into areas where the glass base has already been masked by Al strips. The production of strip waveguide using the double ion exchange technique is presented in Fig. 8. The waveguide is constituted by the area where ion exchange of silver has taken place, and its refractive index is much higher than the refractive index of the area where the exchange of potassium ions has been carried out. On the other hand, the depth at which silver ions are exchanged in the base is smaller than the depth into which potassium ions enter. The waveguide obtained in such a way has an advantage over the waveguide obtained using the standard method. Since the width of the channel is better blocked by the ion mask than by an ordinary metal one, which does not effect such an effective slowing down of ion diffusion on the outside borders of the strip, the application of ion mask results in smaller loss in the waveguide than in the case of metallic mask.

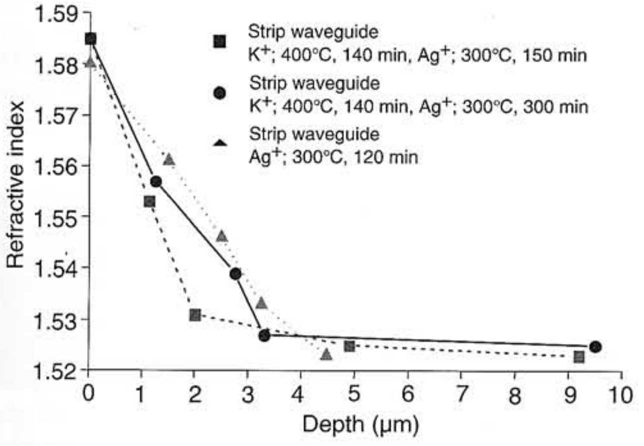


Fig. 9. Refractive profiles of planar waveguides obtained in single and double ion exchange.

Double ion exchange, exchange of potassium ions at the first stage and exchange of silver ions at the second stage is used not only in the masking process. It is used among others for production of diffractive optical elements on planar waveguides. The process makes use of the advantages resulting from the situation where both single-stage processes are carried out. Due to the exchange of silver ions we obtain well-guided modes, what is typical for waveguides produced with the use of technique of potassium ion exchange.

A simple model satisfactorily describing the process of double ion exchange in glass has been offered by Auger and Najafi [6].

It also turns out that the maximum change of refractive index with respect to Ag$^+$ area of double ion exchange is the same [7] as in the case of single ion exchange, which is presented by the Fig. 9.

2.4. Doped glass strip waveguides

In the last few years Najafi *et al.* [8–10] have suggested doping the glass waveguides with rare-earth elements (mainly with erbium) in order to obtain sources (or amplifiers) of light coupled with waveguide structure. Two waveguide configurations were subjected to testing: in the first case, in order to produce a waveguide, ion exchange was carried out in the glass doped with rare-earth elements, and the second configuration was a structure consisting of a waveguide obtained through ion exchange in non-doped glass and glass plate with impurity.

In the first case the ion exchange in glass with impurities results in the modifications of optical properties of the base. In the second case the doped glass is pressed to the waveguide base, with duly selected refractive indexes and other parameters, about 50% of the energy is transferred to doped glass.

Application of ion exchange in neodymium glass resulted in the acquisition of amplifiers and laser at the wavelength 1.06 μm and 1.3 μm (amplification of about 15 dB) [11].

3. Double refraction of glass planar waveguides and their application as sensor

Chemical composition of glass surface is modified by ion exchange. The process of ion exchange not only increases the refractive index on glass surface but also changes other material constants. As a result of ion exchange, also the volume of area near the surface, which is connected with the remaining part of glass, is undergoing changes. The increase or decrease of volume generate compressive or tensile stresses [12,14]. The stresses generated during ion exchange cause double refraction, which can be applied in the integrated optics.

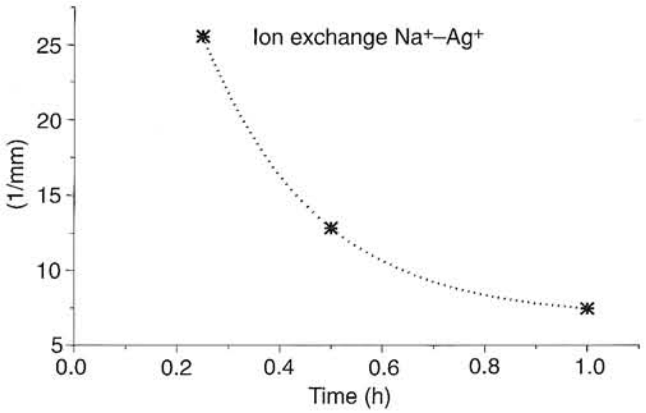


Fig. 10. Determined differences of propagation constants $\Delta\beta_{0Ag} = \beta_{Teo} - \beta_{TMo}$ for waveguides made in the process of ion exchange Na^+-Ag^+ for wavelength 0.67 µm. (Glass BK7, temperature 400°C, times respectively 0.25 h, 0.5 h, 1 h).

Figures 10 and 11 present the differences of propagation constants $\Delta\beta_0 = \beta_{Teo} - \beta_{TMo}$ of zero order modes determined by means of immersion coupler. For the exchange Na^+-Ag^+ the difference for short diffusion times is positive $\Delta\beta_{0Ag}$ and is getting smaller with the time of the process. For longer diffusion times $\Delta\beta_{0Ag}$ is becoming negative (propagation constant of mode TM_0 is higher than the constant of mode TE_0).

In the case of exchange Na^+-K^+ the difference $\Delta\beta_{0K}$ is always negative and its absolute value is increasing with the time of the process. The described above dependencies between propagation constants of waveguide modes for both kinds of ion exchange can be explained by different involvement of two mode dispersion effects and double refraction. If ion exchange did not result in the generation of stresses, the profile of refractive index would be the same for both polarisations. Then, it follows from the solutions of dispersion equations that modes TE_i always have higher propagation constant than modes TM_i. The described effect is being defined as so called modal dispersion.

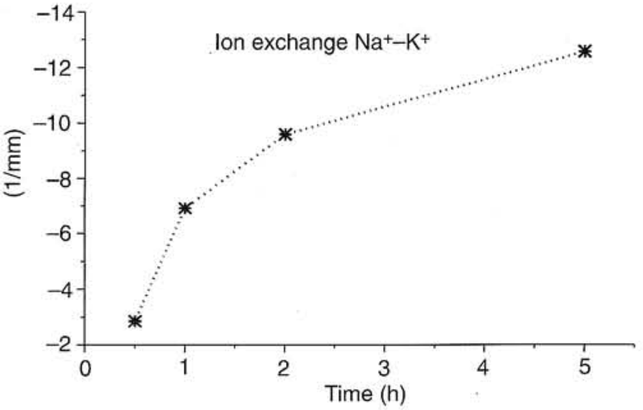


Fig. 11. Determined differences of propagation constants $\Delta\beta_{0K} = \beta_{Teo} - \beta_{TMo}$ for waveguides made in the process of ion exchange Na^+-K^+ for wavelength 0.67 µm. (Glass BK7, temperature 400°C, times respectively 0.5 h, 1 h, 2 h, 5 h).

The process of ion exchange induces stresses. It leads to different refraction profiles for both orthogonal polarisations. In glass BK7 the stresses in both kinds of ion exchange are of compressive character, and hence the refractive coefficient at a definite point for polarisation TM has higher value than for polarisation TE. In consequence, the difference of propagation constants $\Delta\beta_i = \beta_{Tei} - \beta_{TMi}$ can be negative.

For short processes of ion exchange Na^+-Ag^+ the effects connected with double refraction are not dominant, therefore the difference of propagation constants $\Delta\beta_{0Ag}$ is positive. With the increase in diffusion time $\Delta\beta_{0Ag}$ is decreasing and for long diffusion times it becomes negative. It has been observed for diffusion time 12.83 h at a temperature 300°C. The effects connected with double refraction of refractive profile begin to dominate, what results in the change of the sign of the difference of propagation constants. In the case of ion exchange Na^+-K^+ the double refraction of waveguide is a dominant factor from the very beginning of the process, therefore $\Delta\beta_{0K} = \beta_{Teo} - \Delta\beta_{TMo}$ is always negative.

The dependence of propagation constants in planar waveguides on refractive indices, i.e., the base n_s, the waveguide n_f, the cover n_c, the layer thickness W and the frequency ω, has been applied in planar waveguide sensors. Propagation constants are also different for modes TE and TM. The modes differing with polarisation states are described by differing dispersion equations and by different influence of double refraction on propagation constants. By exciting the modes of the same order we bring about the situation where propagation constants β_{TE} and β_{TM}, having different values, effect the phase difference equal to $\Delta\phi$ along the propagation line [15].

4. Equipment and elements based on glass planar waveguides

Double ion exchange due to its advantages, such as:

- small loss of propagation,
- more symmetrical modal profile than in the case of single ion exchange,
- possibility to produce waveguides with so-called double core (which are characterised by two different areas formed by potassium ions and silver ions, which guide light),
- good guiding of modes,
- weak absorption of light in the visible range, permits to produce more sophisticated waveguide structures, and hence also equipment.

Computer generated waveguide holograms CGWHs may serve as an example of such equipment; it was created and tested among others by Saarinen. The formation process of waveguide hologram, to effect the separation of optical beam on 1/8, with the application of double ion exchange, was presented in Refs. 5, 16 and 17. At the first stage of the formation process of the above structure, pla-

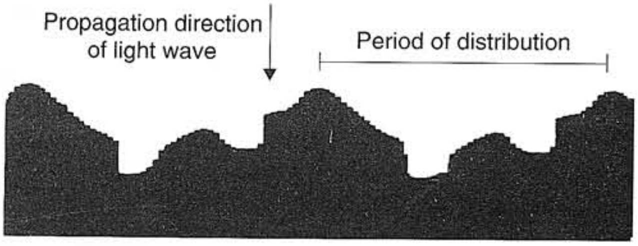


Fig. 12. Periodic CGWH structure enabling the division of light beam on 1/8, made with the technique of double ion exchange (after Ref. 21).

nar waveguide is made on the base Corning 0211 using ion exchange technique K^+-Na^+. Then, its surface is covered by a layer of aluminium mask.

The CGWH structure is fixed on the mask Cr using the laser beam. This model of the mask is transformed into the mask Al with the use of photolithography process, and the exchange Ag^+-Na^+ is carried out. The parameters of ion exchange, temperature and diffusion time are selected in such a way so that after passing the structure of waveguide front the modulation of phase could take place. Figure 12 presents the CGWH structure, which is made up as a grid consisting of 50 rectangular cells of equal width in each period.

In the experimental system the linearly polarised grid was lit with a laser beam He-Ne, which was entering the waveguide through the prism where the mode TN_0 was excited. Then the beam, after being split by CGWH, was leaving through the second glass prism. Figure 13 presents the recorded diffraction pattern. It shows a non-deflected line of the zero order which theoretically should have disappeared. Apart from it, the lines of the following orders appear there: $m = -4, -3, -2, -1, -1, -2, -3, -4$. The intensity of the zero order line results from mismatch of modes TM_0 in the area obtained by different techniques of ion exchange. A part of the light passes to the mode TM_1 of the waveguide obtained as a result of double ion exchange (CGWH) and returns to the mode TM_0 of the waveguide obtained through the exchange K^+-Na^+. These two modes have almost equal effective refractive indices and therefore there is no significant modulation of the phase of mode TM_1 and the light again passes to the non-deflected beam. The line of the order 0 can be eliminated by appropriate designing of the structure CGWH.

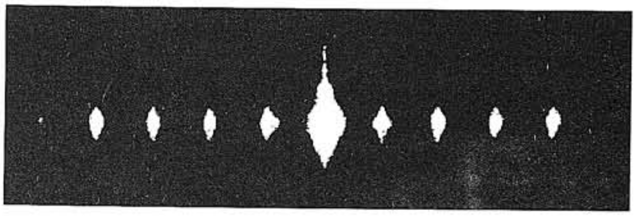


Fig. 13. Diffraction image generated by CGWH. Parameters of the production process of K^+-Na^+ – 45 min, 384°C, Ag^+-Na^+ – 105 min, 300°C, heating time 20 min., temperature 285°C (after Ref. 21).

A lot of works involving the application of double ion exchange for the formation of optoelectronic line have been published recently. Mshayekhi [18] has proposed the element which couples optical fibre with semiconductor waveguide produced on the basis of double ion exchange; the loss at the junction fibre-waveguide element-waveguide was reduced to about 3 dB. Honkonen and Poykonen [19] have proposed adiabatic waveguide coupler of the Y-type made using the exchange technique K^+-Na^+. The loss in this case was reduced to 1.2 dB. Zhang and Honkanen [20] produced, on one base Corning 0211 in the same process, two multiplexers at the wavelength 1.55 µm, and 1.48 µm as well as 1.30 µm and 1.55 µm. Many other applications of double ion exchange for production of systems with multiplexing of wavelength WDM can be found in Refs. 6 and 21.

5. Multimode interference structures in the technology of elements of integrated optics

Multimode interference (MMI) structures have been a subject to intensive research studies for a few years [22,23]. It is a new technology that makes use of the effects of the interference of mode fields in multimode waveguide, which forms a multimode interference section. Intermode interference is accompanied by the so-called events of self-imaging of input field which excites multimode waveguide. As a result of these events, the input field, which is usually effected by a single input singlemode waveguide or a group of singlemode waveguides, is reproduced in simple, reflected and multiple images.

In currently available literature we can come across works involving multimode interference structures made on the basis of step-index waveguides. The work [24] presents the possibility for occurrence of self-imaging in gradient waveguides made by the ion exchange $K^+ \leftrightarrow Na^+$.

5.1. Operating

A diagram of a typical MMI structure is presented in Fig. 14. It consists of a a group of input waveguides (a) that define input field of a wide multimode section (b) where we can observe the effects of interference of mode fields and singlemode output waveguides (c). Singlemode waveguides provide stable distribution of input field $E(x,y,0)$. The field introduced to multimode section is decomposed

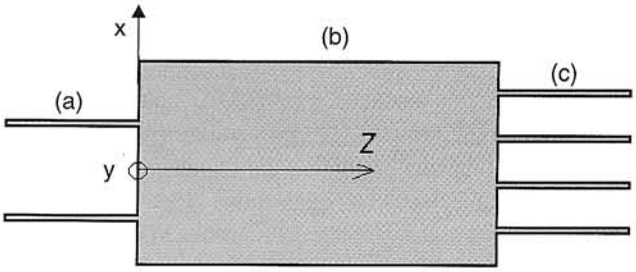


Fig. 14. Diagram of a typical MMI structure.

into mode fields $\phi_{nm}(x,y)$ of multimode waveguide, of propagation constants β_{nm}

$$E(x,y,0) = \sum_{n,m} c_{n,m}\phi_{n,m}(x,y). \tag{7}$$

The field at the distance z from the introduction point is the superposition of mode fields, which propagate with different phase velocities and therefore they are in a different way shifted in the phase

$$E(x,y,z) = \sum_{n,m} c_{n,m}\phi_{nm}(x,y)\cdot\exp(-j\beta_{nm}z). \tag{8}$$

The image of interference of mode fields observed in the section MMI depends on mode properties of multimode waveguide. Gradient structures made using the technique of ion exchange in glass seem to be particularly interesting for the technology MMI. Due to ion exchange technique which makes use of multi-stage processes of diffusion, electrodiffusion, diffusive and electrodiffusive burying, we can very freely form mode properties of the obtained waveguides which decide on the effects of intermode interference.

The present work demonstrates theoretical research studies using the beam propagation method (BPM) of multimode gradient interference structures made in a simple diffusion $Ag^+ \leftrightarrow Na^+$ to the glass base plate, in view of their application in the systems of integrated optics.

5.2. Self-imaging events in gradient waveguides

The basic element of the investigated gradient MMI section is made up by a multimode waveguide made using the ion exchange $Ag^+ \leftrightarrow Na^+$, of the distribution profile of refractive index calculated numerically on the basis of nonlinear diffusion equation [25], for the window 16 μm wide. The base was made up by borosilicon glass ($n_0 = 1.51$) surrounded by air. The following material parameters were used in the calculations: diffusion depth of ions Ag^+ = 0.31 μm, mobility ratio of exchanged ions $r = 0.5$ and maximum change of refractive index $\Delta n = 0.1$. For selected in such a way geometry and parameters of technological process, as it can be presented on the basis of the method of effective refractive index, the waveguide is singlemode for the direction being in agreement with the width of structure x (it guides 12 modes), and singlemode for the perpendicular direction y. Therefore unidimentional effects of the interference of mode field will occur.

Figure 15 presents the evolution of normalised amplitude of the field of wave A(x,y) determined by the BPM method [24], for the structure MMI excited symmetrically with the field of singlemode waveguide, obtained during the diffusion through the window 1.2 μm. The distribution presents contour map of the amplitude along propagation way for the minimum reference level 0.25 of maximum value. In such a situation only even modes MMI should get excited. The image of input field is formed at the distance L = 650 μm. At the distances L/n symmetrical n-fold images of input field are observed. At the distance z = 170 μm from the introduction place, the input field is divided into four almost equal parts, which means that MMI can be applied as power divider 1×4. Power division can be obtained for the propagation length z = 329 μm. After passing a section twice as long, a simple image of the input field appears.

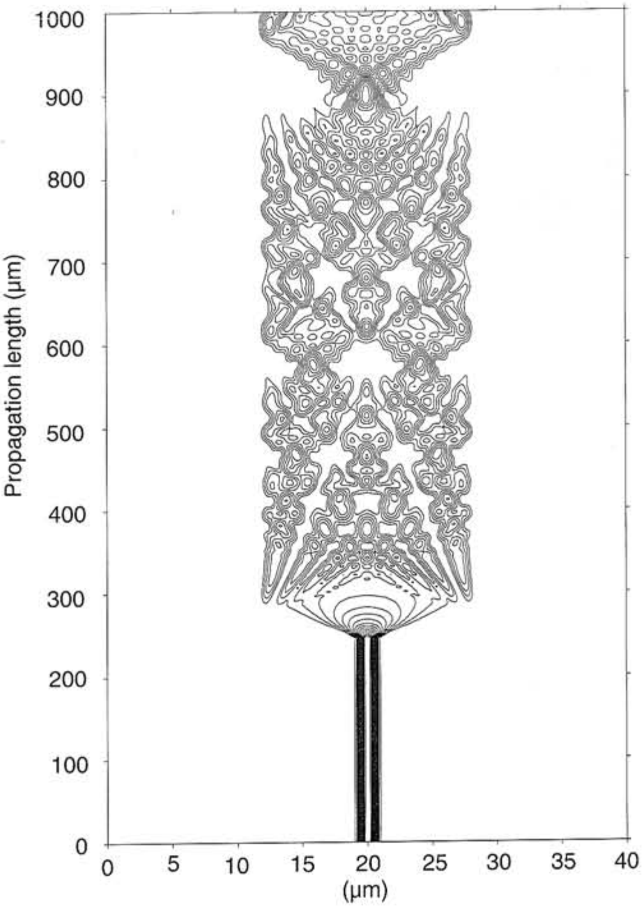


Fig. 15. Evolution of normalised amplitude of the field.

As it can be seen, the observed interference images recreate the input field only approximately. The quality of interference images is getting worse also with the increase of propagation area.

5.3. Waveguide T-junctions based on MMI

Making use of the self-imaging effects of input field we can produce T-junctions and couplers 1×N and N×M having very good optical parameters, where the branching of input field is realised on a very small area of a few hundred μm. Figures 16 and 17 present numerical simulations, using BPM method, of exemplary applications of MMI made with the exchange technique $Ag^+ \leftrightarrow Na^+$ for the realisation of symmetrical T-junction 1×2, for which we obtain at the output a uniformly divided signal of the value 0.65 of input field (total attenuation 0.714 dB) and of the T-junction 1×4 of the output 0.455, 0.451, 0.457, 0.452 (attenuation 0.85 dB). The value of output signal is influenced by the

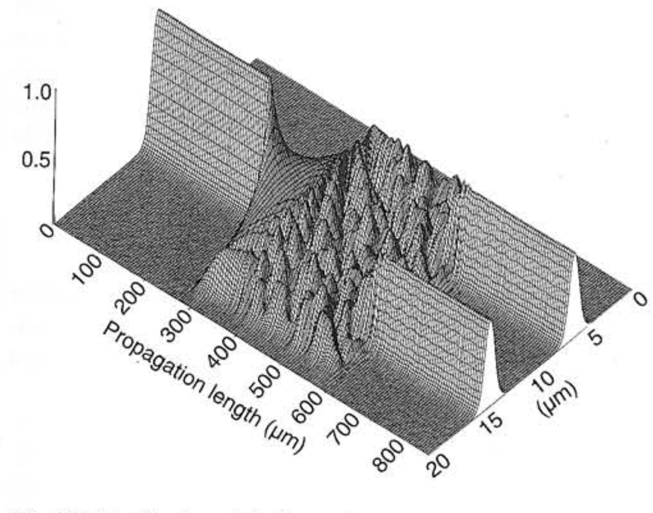


Fig. 16. Distribution of field amplitude in waveguide T-junction 1×2.

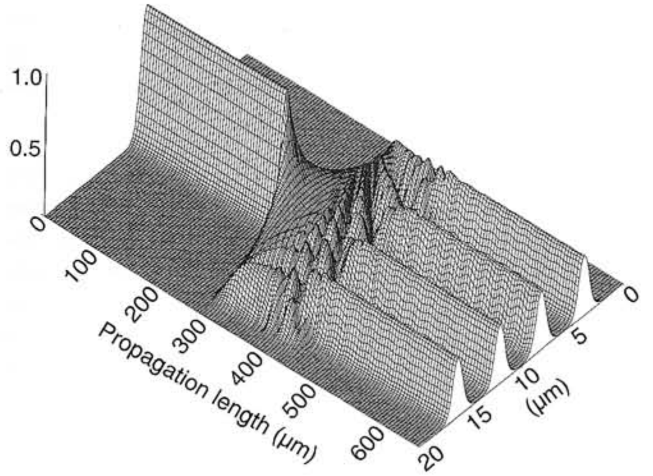


Fig. 17. Distribution of field amplitude in waveguide T-junction 1×4.

quality of self-imaging of input field and the loss of field coupling at the output of MMI with singlemode waveguides.

Figure18 presents a more complex optical system of Mach-Zehnder interferometer where MMI elements were used for branching of input field and coupling of signals from both arms of the interferometer. The signal at the output had the value 0.84 of the input signal (total attenuation 1.42 dB). A similar method can be applied for realisation of Mach-Zehnder interferometers of larger number of arms.

5.4. Application potentials of MMI in the technology of waveguide sensors

Gradient MMI can be also applied in the systems of waveguide sensors. The change of external conditions of wave propagation, connected with the presence of dielectric layers covering the whole area or a fragment of multimode interference section and changing optical properties when affected by external physical fields or chemical absorption, can be recorded in the changes of interference images of mode fields. The division of wide multimode interference structure into the sections covered by the strips of layers sensitive to various measurement values may be applied in the production of interference sensor for simultaneous detection of several values. Introductory numerical simulations show the sensitivity of multimode interference in gradient multimode structures to slight (of the order 0.5×10^{-4}) changes of refractive index of dielectric layer.

6. Plasmon interaction in planar structures

Over the last two decades, the literature all over the world has been providing information involving the application of surface plasmon resonance (SPR) in many electro-optical units. To provide some examples, we can mention such as: modulators of light intensity, spatial modulators of light, bistable facilities, units for the generation of second harmonic, tunable optical filters. And the last decade brought forth information on the application of SPR for sensor related purposes. In the beginning, the units were built on the basis of Kretschmann's configuration (volumetric), and recently the literature has provided examples for the application of cylindrical and planar waveguides for the construction of gas sensors with the use of SPR.

Along the border between metal and dielectric, the surface plasmon wave, so-called surface plasmon, can be excited. Optical properties of metal are described with dielectric permittivity $\varepsilon_m = \varepsilon_{mr} - \varepsilon_{mi}$, and properties of dielectric with permittivity ε_1. Let the electromagnetic wave of the wave number k_0 and polarisation TM falls on the border between the media. Along this border the surface plasmon wave can be excited (in electron plasma of metal). The easiest way to excite plasmon wave is with the assumption that $\varepsilon_{mr} < 0$, $|\varepsilon_{mr}| >> \varepsilon_{mi}$, $|\varepsilon_{mr}| > \varepsilon_1$, then the real part of wave number of surface plasmon [26]

$$k_r = k_0 \sqrt{\frac{\varepsilon_1 \ \varepsilon_{mr}}{\varepsilon_1 + \varepsilon_{mr}}} > k_0 \sqrt{\varepsilon_1} \ . \tag{9}$$

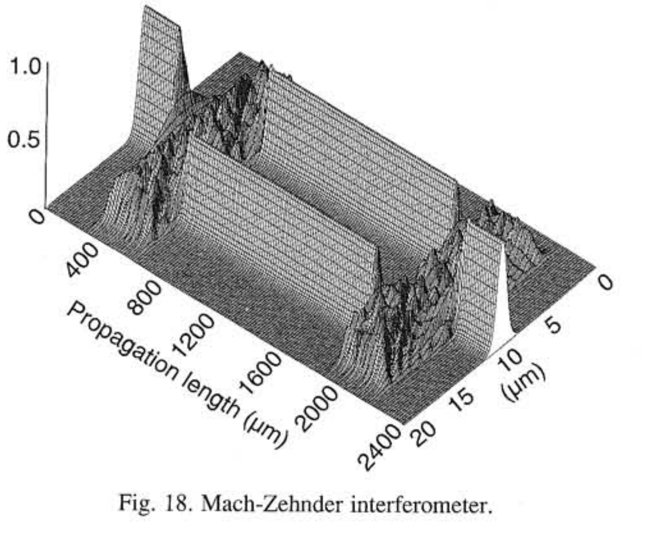


Fig. 18. Mach-Zehnder interferometer.

It results from the above that the border along which surface plasmon can propagate must divide the media whose real parts of dielectric constants have opposite signs, whereas the imaginary part of dielectric constant of metal should be small (so that permittivity could be small). Attenuation of such surface waves is very high and their range is from several to a dozen or so micrometers. The penetration range under and over division surface of the media is still smaller and can equal several dozen nanometers. Surface plasmons always have polarisation TM. As it results from Eq. (9), the real part of wave number of surface plasmon is higher than the wave number of light wave in dielectric medium. In order to effect the coupling of light wave propagating in dielectric medium with surface plasmon (its exciting by light wave), equality of both wave numbers must be ensured. It is of consequence when considering the excitement ways of surface plasmons. In order that the excitement of plasmon wave could take place, the exciting electromagnetic wave must contain a mode of the wave number $k_x = n_1 k_0 = \sin\theta_i$, satisfying the condition $k_x = k_r$. This condition can be satisfied by changing the angle θ_i or the length of the exciting wave, since the values ε_{mr}, ε_l depend on wavelength.

The structure of waveguide sensor based on the surface plasmon resonance was schematically presented in Fig. 19.

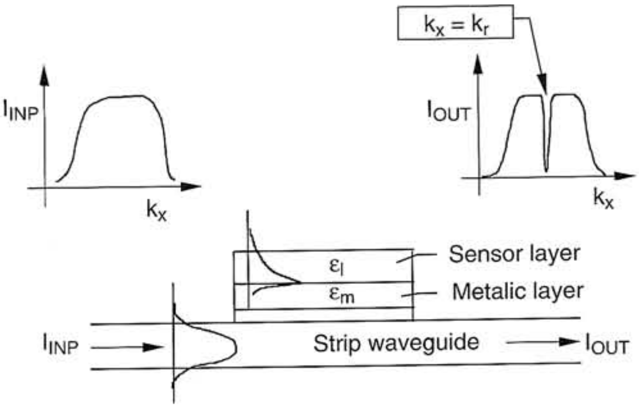


Fig. 19. Concept of the structure of plasmon sensor.

Strip waveguide can be both of single- and multimode character. Polychromatic light is introduced to the waveguide. By propagation, the light effects the excitement of surface plasmons. They can be excited only by the wave having the length which satisfies the condition of phase synchronism. Observing the spectral composition of light reaching the sensor's output we can make assumptions on the length of wave which has been decoupled and which excited the surface plasmon. Since the length of this wave is the function of ε_m and ε_l, therefore we can in this way measure with high sensitivity the refractive index of the medium located over the metallic layer (with constant ε_m). It is required from the dielectric sensor layer that it should change its refractive index in the function of concentration, e.g., of gas which it has adsorbed. The thickness of this layer should be very small (of the order of several dozen nm) due to two reasons: so that the sensor's response was burdened with small time constant, and that the electric field of surface plasmon could penetrate through its whole thickness.

7. Conclusions

The technology based on ion exchange in glass has been known for many years. At first, the technology was developing slowly, and its application perspectives were limited to passive elements (T-junctions, couplers, etc.).

Over the last decade, the technology has started to develop intensively and the application potentials have increased considerably. Double ion exchange, waveguide burying, doping with laser elements, application of ion exchange in borosilicon glass offered new application possibilities, not only in passive elements but also in units in monolithic connection of waveguide structures with the sources or amplifiers. The development of ion exchange technology made it possible to join waveguide structures with quantum dot waveguides [27].

Ion exchange technique has been widely applied in telecommunications, particularly in local and computer networks as well as in sensor related technology. The paper has demonstrated expanding application potentials in new kinds of sensors, e.g., plasmon sensors. Over the last five years the production technology of T-junctions 1×N, double wave multi- and demultiplexers has been developed sufficiently enough to be introduced to industrial mass production [28].

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