Optica Applicata Vol. X, 2, 1980

Planar dielectric light-waveguide produced by the method of ion exchange

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In this work the method of formation of planar optical waveguides is presented which is based on exchange of ions Na^+ from surface region of substrate glass plate and Ag^+ from liquid $AgNO_3$ which is in contact with the surface of substrate plate. By use of this method the following structures were formed: planar optical waveguides with different propagation capabilities and low attenuation (from 1.3 to 2.4 dB/cm at $\lambda = 632.8$ nm for TE_0 mode), stripe waveguides, mode selector and tapered film coupler. The results of studies of the formed structures are presented.

Introduction

Planar light-guides are basic elements of the integrated optoelectronic systems. They offer not only a medium for electromagnetic wave propagation and guiding, but also create a basis for the construction of majority of passive and active structures as well as functional systems. The substance creating a light-guide must posses a definite optical properties and in many cases meet also some electro-, magneto- and acoustooptical requirements. Thus the number of materials used for light-guides is very great. Independently, a large variety of methods for light-guiding layers production is used. Hence, the family of light-guides is extraordinary numerous.

The light-guide is a dielectric element "immersed" in a substrate and produced by impurity penetration into the surface layer of the plate. This impurity increases the refractive index of the substrate material in this region.

Production of light-guides

The method of ion exchange, called also the diffusion method, was applied initially to production of light-guide glass fibres (the so called Selfoc Fibers) [1], and next — with some modifications — to the formation of film light-guides [2, 3]. This method consists in the exchange of the Na^+ ions of the glass modifier into Ag^+ ions coming from the fluid phase of $AgNO_3$; the latter being in contact with the plate surface.

The glass playing the part of the substrate material must include pretty high concentration of NaO_2. In the course of the experiments two sorts of soda-lime glass were exploited. One of them, i.e. that used for the microscopic plates and containing about 7.5% of CaO and 15% Na_2O was the glass of Polish make. The other was the glass of Belgian Agfa Gevaert firm of similar chemical composition. Both the materials have the refractive index $n_s = 1.512$ at $\lambda = 632.8$ nm*. The silver nitrate used in the exchange processes was of 99.8% purity level.

* All the other numbers defining, hereafter, the values of the refractive index and attenuation refer to this light wavelength.

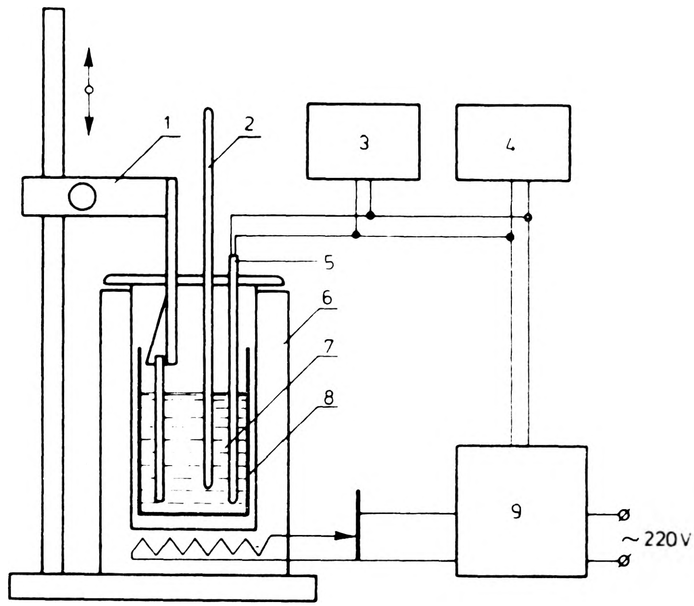

Fig. 1. Scheme of the apparatus for light-guide formation by the ion exchange method: 1 — chuck with the substrate, 2 — mercury termometer, 3 — recorder, 4 — temperature indicator, 5 — thermo-couple, 6 — furnace, 7 — silver nitrate, 8 — Al crucible, 9 — RL3 controller

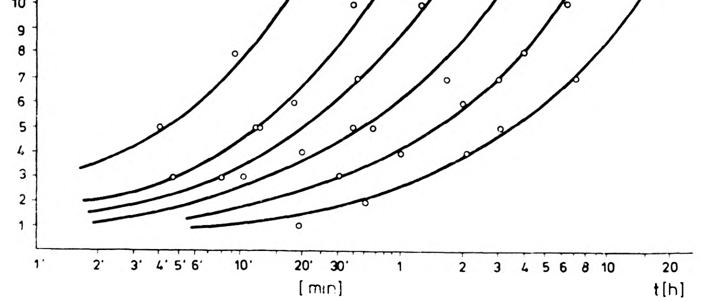

Fig. 2. Propagation properties of the light-guide vs. the technological parameters process: $N = m+1$ — number of transferred modes, $m = 0, 1, 2, \ldots$ — mode orders

The $AgNO_3$ fluid, being an unlimited source of Ag^+, was produced in an aluminium crucible inserted in a furnace in which the temperature was controlled with the accuracy to ± 1.5 deg. The glass plate — after suitable preparation of its surface — was immersed and kept in an $AgNO_3$ bath. The scheme of the apparatus, in which the processes of ion exchange were carried out, is shown in fig. 1.

The diffusion process parameters are (as usually in this method) the temperature and time. They determine the speed and depth of penetration of diffusing particles. The experiments for both the glass sorts were performed within the 493-623 K temperature range for the time ranging between 5 and 420 min. As a result of numerous attempts a technological process of high repeatability, assuring a unique correlation between the above parameters and the propagating properties of the waveguide, has been elaborated. These dependences, being the most essential experimental result, are presented in fig. 2. The picture shows a set of characteristics $N(t)_{A,T=\mathrm{const}}$, where t — time, T — temperature, A — material constant. These characteristics as well as the value of constant A were determined experimentally. The parameter A is also temperature-dependent. The dependences of A vs. t were also determined experimentally, and proved to fulfill the analytical relations of exponential type

$$A = 1.15\times 10^{-3}\exp\,(1.6\times 10^{-2}\,T) \quad \text{— for glass of Polish make}$$

$$A = 1.57\times 10^{-3}\exp\,(1.88\times 10^{-2}\,T) \quad \text{— for Agfa Gevaert-firm glass}$$

The parameters of curves $N(t)$ are pairs of uniquely associated values in accordance with the above equations.

The result of examination

By exploiting the presented technological method several thin-film structures have been produced and their properties examined.

The most attention has been drawn to the planar light-guide. On the basis of $N(T)_{A,T}$ characteristics two families of light-guides, one for each glass sort, have been produced for the prescribed values of N ranging between 1 and 10. The layers obtained have been examined in many respects with the help of specially designed measuring system.

The attenuation responses of light-guides, i.e. the $P(x)$ responses (where x is a coordinate in the direction of propagation, and P denotes the beam power) have been determined. They are exemplified in fig. 3. From these responses the light-guide attenuation may be immediately determined, since this is, in fact, the slope of the respective response expressed in dB/cm. The values of this parameter are given for all the curves appearing in the picture. The lower part of fig. 3 presents an experimental illustration for the importance of the reflecting surface roughness. Minimal attenuation for $m = 0$ was: 2.4 dB/cm — for waveguide formed in the microscopic glass, and 1.3 dB/cm — for the layers in Agfa Gevaert-firm glass.

In fig. 4 a multimode light-guide, excited with the help of prism coupling, is shown. The excitation starts at the left-hand side of the plate. A prism leading out the radiation from the waveguide is seen on the right-hand side.

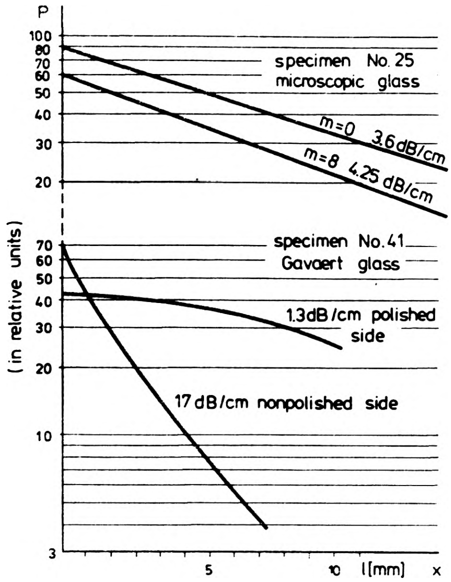

Fig. 3. The attenuation characteristics for the selected light-guides, l — distance between the points of the exciting and leading out couplers

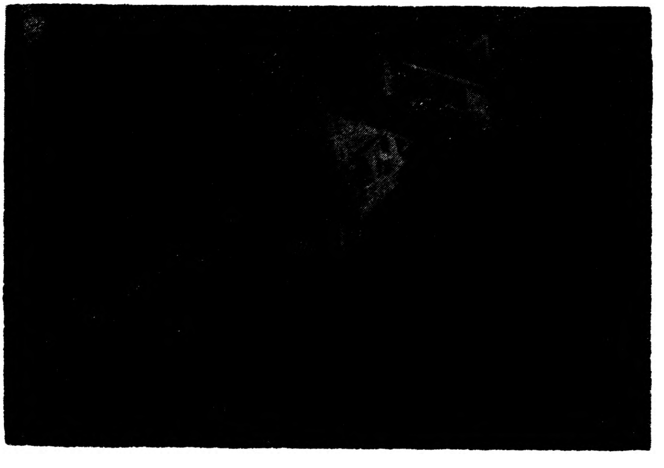

Fig. 4. Multimode light-guide in operation

Fig. 5 presents a pattern of 7 modes ($m = 0$ - 6) led by this waveguide as it appears on a screen. In the multimode light-guides the synchronous coupling angles have also been measured for modes of definite orders. The results of these measurements allowed to determine the respective values (for $m =$ const.) of the effective refractive index, according to the relation

$$n_e = \sin\alpha\cos\varepsilon + (n_p^2 - \sin^2\alpha)^{1/2}\sin\varepsilon,$$

where: $n_e = \beta/k$ — effective refractive index of the layer,
α — synchronous coupling angle (m = constant),
ε — convex angle of the prism,
n_p — prism refractive index.

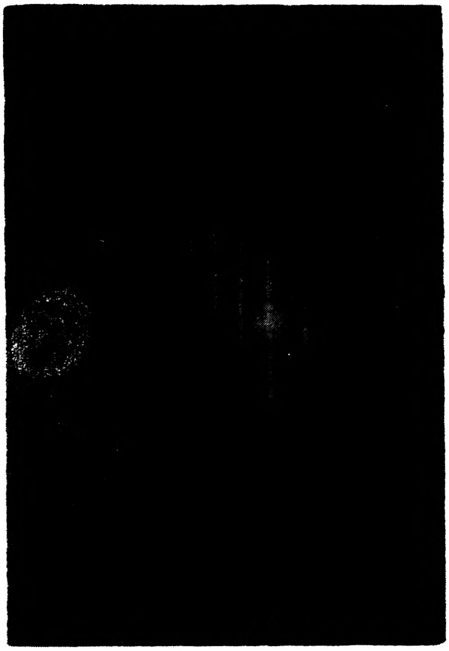

Fig. 5. Mode pattern of radiation transferred by a light-guide shown in fig. 4 (light-guide was excited by the first mode $m = 1$)

The knowledge of the effective refractive index allowed, in turn, to determine the impurity profile and effective thickness of the layer created by the diffusion process.

The next thin-film element, which has been realized was a stripe light-guide. By applying the masking of the glass plate with a thin aluminium foil the stripe light-guides of 25, 70 and 130 μm wide have been formed. These were the multimode light-guides similar to the planar light-guides with respect to their propagating properties, but with slightly greater attenuation — amounting to 3.4 dB/cm in the subsequent cases (for $m = 0$).

Basing on the planar light-guide presented a so-called mode selector has been produced. This is planar light-guide consisting of a single-mode part and a multimode part both being transfered mildly into one another. The technological process was based on the $N(t)_{A,T}$ characteristics. The selected temperature was $T = 448$ K. For the multimode part $N = 7$ ($m = 0-6$) was accepted, while the value of the variable associated to this number was $t = 175'$. For the single-mode layer t was equal to $6'$. The programme for selector formation was the following:

Initially the plate was immersed to 1/2 of its length and kept in the bath for $169'$, next the plate was immersed to 3/4 of its length and kept in the same bath for another $6'$. The two said parts of the light-guide obtained in this way, were transferred into one another with the help of a wedge. The propagation characteristics of this structure have been examined. The light-guide, when excited to multimode operation from the thicker side, carried over only the basic mode $m = 0$ to the output, being however, excited in the same way but from the other side it gave a seven mode pattern at the output in the thicker part, while the power carried over in the fundamental mode was 10 times higher than that in each of the remaining 6 modes.

The wedge section of the layer, joining both the parts of selector, was produced in the region of a concave meniscus, which is formed, close to the fluid surface, when the plate is immersed in the bath. The height of this meniscus amounts approximately to 300 μm, which corresponds to some hundreds of red light wavelengths. In this region there exist both concentration and temperature gradients. Due to these effects a wedge of the length close to the height of the meniscus is formed at the end of the diffusing layer.

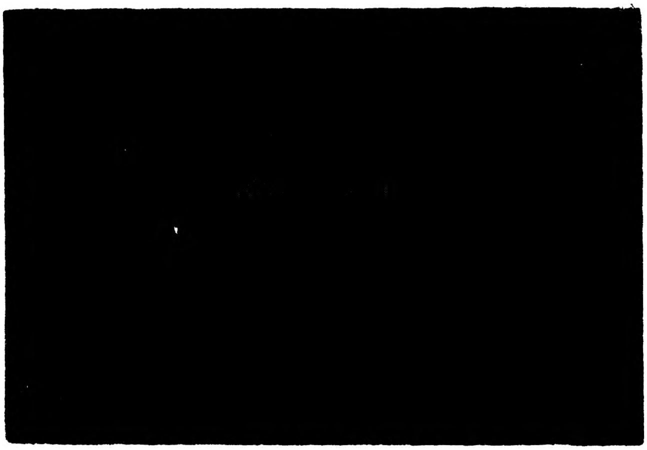

Fig. 6. The excited light-guide with the operating wedge coupler

This experience has been exploited to construct the subsequent element, i.e. the coupling wedge. It has been realized at the end of the 7 mode light-guide distant by several milimeters from the plate end. Next the plate was cut out and polished at a distance of 3 mm from the wedge end. The attempts to change the waveguide modes into the substrate modes appeared to be succesful. On the basis of the beam pattern on the screen the size have been estimated to be equal to 0.4×0.6 mm. The beam of such transversal size is suitable for light-guide coupling with the fibre, the latter, being with the substrate under a proper angle to the light-guide plane. Fig. 6 shows a light-guide excited by a prism (from the left-hand side) with an operating wedge coupler. The place, at which the transition of light-guide modes into those in the substrate occurs, is identical with the end of the shining channel.

Conclusions

The technological methods as well as the results presented in the form of a planar light-guide of low attenuation (1.3 and 2.4 dB/cm), a stripe light-guide, a mode selector and wedge coupler allowed to start the experimental investigations in the field of integrated optoelectronics. In particular, this renders a possibility of further examinations of other types of passive structures as well as of designing the basic functional systems. The specific measurement techniques may also be further developed.

References

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Received, April 18, 1979

Планарный диэлектрический светопровод, изготовленный методом ионного обмена

Описана технология изготовления планарных диэлектрических светопроводов методом обмена ионов. Ионы Na^+ модификатора из близповерхностного слоя стекла заменяются ионами Ag^+, происходящими от жидкой фазы $AgNO_3$, контактирующей с поверхностью стеклянной пластинки. Используя практически освоений технологический процесс были выполнены: планарные светопроводы с различными распространяющими способностями и с малым коэффициентом звукоизоляции (1,3 и 2,4 дБ/см при $\lambda = 6328$ Å для TE_0), дорожечные светопроводы, селектор модов, а также клиновой спрягающий элемент. Представлены также результаты исследований этих структур.