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Some optical properties of planar light waveguides formed by silver-ion diffusion in glass

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Complex propagation constant $\gamma_m = \beta_m + j\alpha_m$ of light waves modes in planar Ag-diffused glass waveguides has been measured. Fitting of experimental and theoretical (WKB method) mode characteristics has offered a possibility to determine refractive index of waveguide. Results are consistent with electron microprobe analysis of silver concentration profile.

1. Introduction

The diffusion process allows to obtain planar and streap waveguides in different materials, such as $LiNbO_3$ [1, 2], which have interesting elasto-optic, electrooptic, magnetooptic or piezoelectric properties. There is a group of integrated optics elements, like directional couplers, couplers between waveguides and fibers, planar polarizers, lenses, etc., which can be formed in “passsive” materials such as glasses.

Investigations reported in this paper concern the characteristics of silver-diffused planar optical waveguides which enable to relate the mode propagation characteristics to the parameters of the diffusion process. Their optical losses have been also determined by measuring the scattered light intensity from waveguide to air.

2. Formation of the planar diffusion waveguide by ion-exchange diffusion of silver into glass

Several experiments based on many reports concerning ion-exchange diffusion of silver into glass were carried out in order to obtain the planar diffusion waveguides. Microscopic slides — made of soda lime glass — were used as substrates. Their refractive index value, estimated from the measurements of Brewster angle, was found to be 1.512 for $\lambda = 0.6328$ µm. The diffusion was formed by immersing glass plates into molten $AgNO_3$ at the temperature ranging from 473 K up to 573 K. At the temperature above 573 K the damages of the glass surface were observed. The duration of the process ranged from several minutes to several hours.

In order to determine the silver concentration profile and its dependence on the process temperature the waveguide samples were examined by means of the electron microprobe X-ray analyser. The samples examined were sliced perpendicularly to the diffusion layer plane; one side of each slice was polished and covered with very thin carbon film. Figure 1 represents one curve of silver concentration profile shown in the scanning electron microscope picture, the sodium ions concentration profile curve in the same sample being given in fig. 2. These two photographs confirm that diffusion process of silver into glass is based on Ag and Na ion exchange.

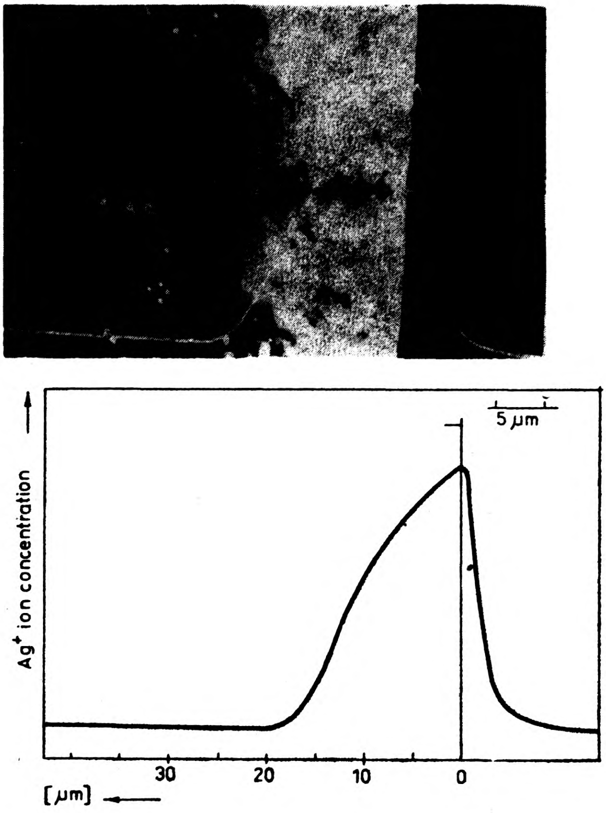


Fig. 1. Silver concentration profile obtained from electron microprobe analysis of a cleaved waveguide sample. Diffusion time 144 min., temperature 568 K

Assuming that the index change Δn is proportional to the Ag ion concentration and basing upon the obtained profile curves and results of experiments presented in [3] it has been established that refractive index profile of the waveguide has the form of a quadratic polynomial

$$n_1(y) = n_s - \Delta n_s \left[\left(\frac{y}{2\sqrt{D \cdot t}} \right) + b \left(\frac{y}{2\sqrt{D \cdot t}} \right)^2 \right], \tag{1}$$

where y is diffusion direction perpendicular to waveguide plane, D, and t are constant and diffusion time, respectively, $n_s = n_1(0)$ is the index value at the surface waveguide. Because the value of D is temperature dependent then from the formula

$$D = D_0 \exp\left[-\frac{\Delta E}{RT}\right]$$

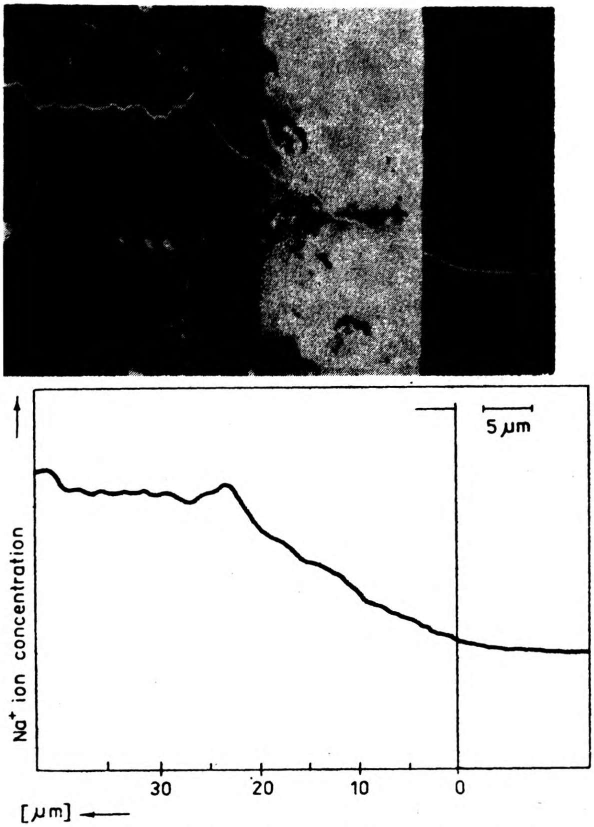


Fig. 2. Sodium concentration profile in the same sample as in fig. 1

we get $D_0 = 2.26 \cdot 10^{-6}\ \mathrm{m^2\,s^{-1}}$, while $\Delta E = 8.5 \cdot 10^7\ \mathrm{J\,kmol^{-1}}$ is found by determining Ag concentration profiles in various times and temperatures and using the dependence $2\sqrt{D \cdot t} = L$, where L is length of diffusion path. The above data fairly well agree with the results given in [3].

3. Determination of mode characteristic and investigation of some optic properties of waveguides

Characteristic equation (2) describes light wave propagation in the planar waveguide

$$\int_0^{y_t} \sqrt{k^2[n_1^2(y) - (\beta/k)^2]}\,dy = \Phi_{10} + \Phi_{12} + m\pi, \tag{2}$$

where $m = 0, 1, 2 \ldots$ is mode number, $2\Phi_{12}$ is the phase change occurring during reflection at the upper glass-air interface given by [4]:

$$\Phi_{12} = \operatorname{arc\,tan}\sqrt{\frac{(\beta/k)^2-n_2^2}{n_s^2-(\beta/k)^2}}, \quad \text{for TE modes,} \tag{3}$$

$$\Phi_{12} = \operatorname{arc\,tan}\left(\frac{n_s}{n_2}\right)^2\sqrt{\frac{(\beta/k)^2-n_2^2}{n_s^2-(\beta/k)^2}}, \quad \text{for TM modes,} \tag{4}$$

$2\Phi_{10} = \pi/2$ is the phase change due to reflection at the lower waveguide interface, $k = 2\pi/\lambda$, β is real part of complex propagating constant, n_0, $n_1(y)$, n_2 are refractive indices of substrate, waveguide and superstrate (air), respectively, y_t is the WKB turning point defined by

$$n_1(y_t) = \beta/k, \quad \text{because} \quad \sqrt{k^2[n_1^2(y_t)-(\beta/k)^2]} = 0.$$

If the value $n_s = n_1(0)$ is determined is some way the right side of the eq. (2) may be presented on a diagram as a function of β/k with the mode number m as a parameter. The values β_m/k of each mode can be found by plotting on the same diagram the numerically calculated left side of eq. (2) as a function of β/k, assuming a refraction index profile $n_1(y)$. This diagram for $n_1(y)$, of the same form as in eq. (1), is shown in fig. 3.

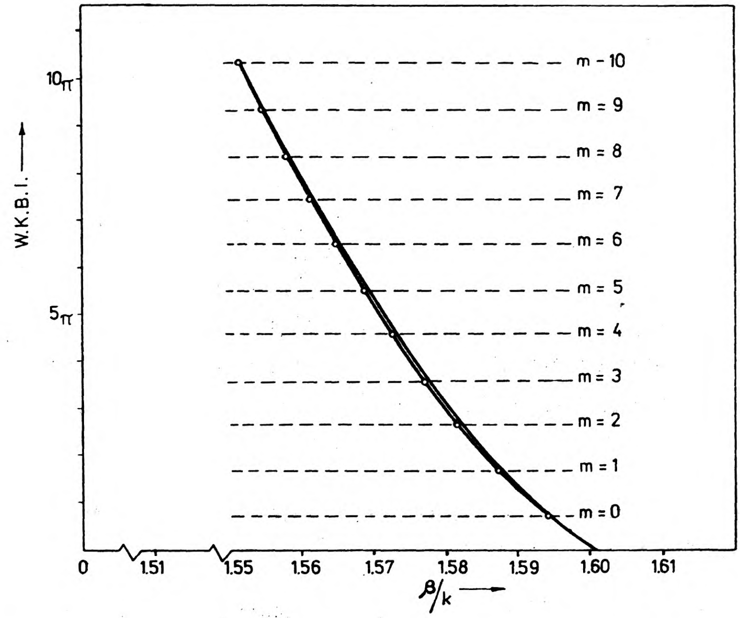


Fig. 3. Experimental mode indices compared with the function β/k computed from WKB integral when $n_1(y)$ is second-order polynomial function. Diffusion time 364 min., temperature 568 K

To fit calculated values of β_m/k with those obtained experimentally the least-mean-square error method was used with respect to the "*b*" parameter from eq. (1).

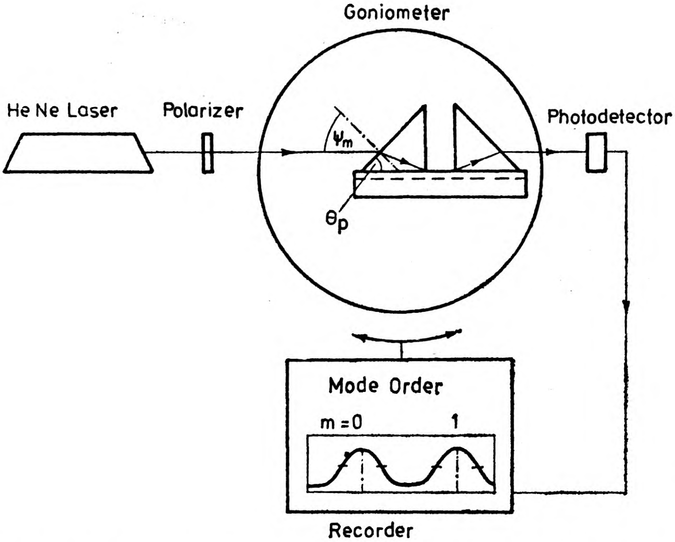


Fig. 4. Block diagram of the arrangement used for measurement of the effective mode indices

The constant value of real part of propagation was determined by measurements of the synchronous coupling angles Ψ_m of the prism copuler (fig. 4), using the relation [5]

$$\Psi_m = \arcsin\left\{\frac{n_p}{n_2}\sin\left[\arcsin\left(\beta_m/k\cdot n_p\right)-\theta_p\right]\right\}, \tag{5}$$

where n_p is prism refraction index, and θ_p is prism angle. When the incidence angle is equal to one of synchronous angles Ψ_m inside the waveguide, then beside the main mode m there occur also other "scattered" modes, caused by the light beam scattering and nonparallelity of laser beam.

Hence, by replacing the photodetector behind the output prism coupler by the photographic plate we get the full mode spectrum record of the investigated waveguide. TE_m mode spectrum for one of the waveguides is shown in fig. 5.

It has been found that TE_m and TM_m modes of the same order are shifted reversely to the shift of modes expected from characteristic equation. It is caused by the temporary double refraction induced by clamping the prism to the waveguide surface. Practical arrangement of prism coupler is shown in fig. 6. Table 1 presents the theoretically and experi-

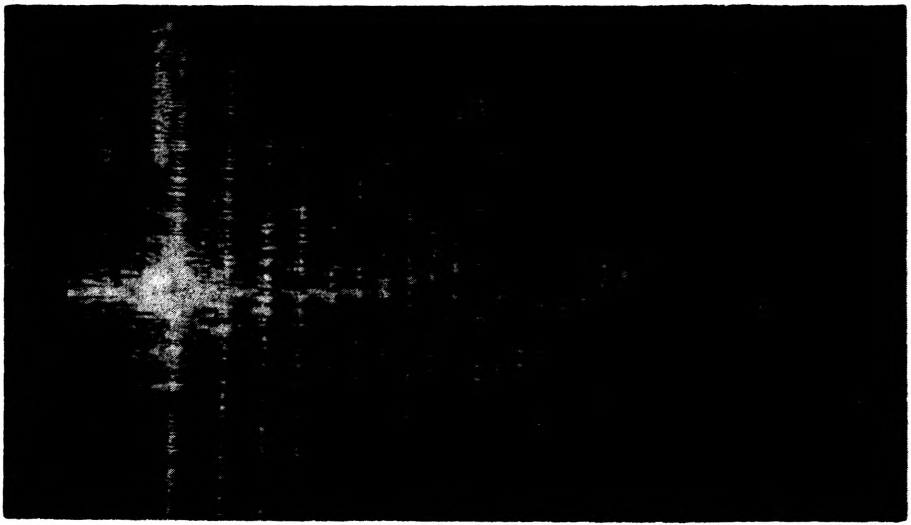


Fig. 5. TE mode lines resulting from decoupling of the light energy from the optical waveguide. Diffusion time 364 min., temperature 568 K

Table 1. Comparison between the observed and theoretically calculated (WKB method) propagation constants of the Ag diffused waveguide. Diffusion time t = 364 min., temperature T = 568 K. WKB calculations for: $n_s = 1.6016$, $n_0 = 1.512$, $n_2 = 1.0$, $b = 0.64$, $\lambda = 0.6328$ μm.

Mode order m	Propagation constant			Deviation $\times 10^{-4}$
	Observed		Theoretical	
	a_m [dB/cm]	β/k	β/k	
0	5.1238	1.5941	1.5942	+1
1	5.1626	1.5877	1.5881	+4
2	5.4748	1.5822	1.5831	+9
3	5.0082	1.5775	1.5785	+10
4	4.3101	1.5731	1.5731	+11
5	5.0938	1.5691	1.5701	+10
6	4.1402	1.5654	1.5661	+7
7	5.3005	1.5617	1.5623	+6
8	5.4923	1.5583	1.5586	+3
9	4.9930	1.5547	1.5550	+3
10	5.6182	1.5515	1.5515	0.0

mentally obtained values of β_m/k ratio compared for waveguide produced at the 568 K during 264 min. Theoretical calculations were carried out by assuming the form of $n_1(y)$ from eq. (1), and the value of $b = 0.64$. It seems that theoretical to experimental data fit is quite good, not exceeding

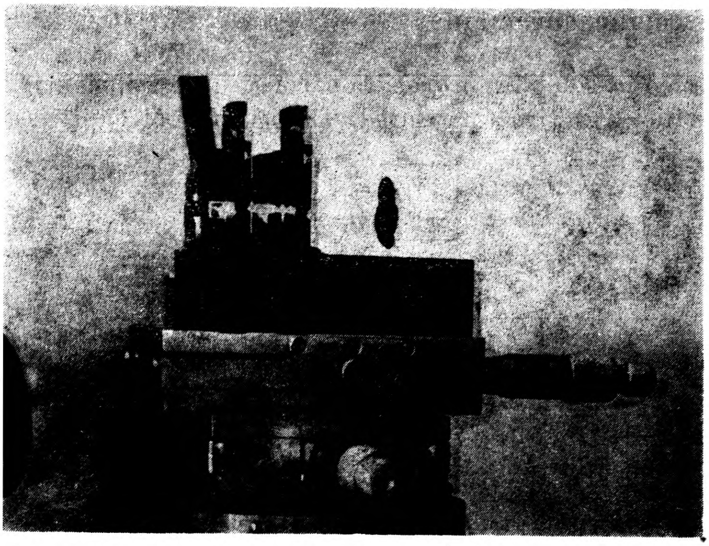


Fig. 6. Practical arrangement of prism coupler

Table 2. Mode indices of the waveguide calculated theoretically (WKB method) for different diffusion temperatures. The remaining diffusion and waveguide parameters are the same: diffusion time $t = 364$ min., $n_s = 1.6016$, $n_0 = 1.512$, $n_2 = 1.0$, $b = 0.64$. Light wavelength $\lambda = 0.6328$ μm

Mode order m	β/k		Deviation $\times 10^{-4}$
	T = 567 K	T = 569 K	
0	1.5941	1.5943	+2
1	1.5881	1.5883	+2
2	1.5829	1.5834	+5
3	1.5782	1.5788	+6
4	1.5739	1.5744	+5
5	1.5697	1.5705	+8
6	1.5657	1.5665	+8
7	1.5619	1.5628	+9
8	1.5581	1.5592	+11
9	1.5545	1.5555	+10
10	1.5509	1.5521	+12

admissible error limits due to the temperature fluctuations during diffusion process. For instance, the differences of mode characteristics due to fluctuations of temperature ranging within 568 ±1 K are shown in table 2.

4. Waveguide losses measurements

In order to determine the complex propagation constant, its imaginary part, i.e. the loss coefficient a_m was measured. This coefficient expressed

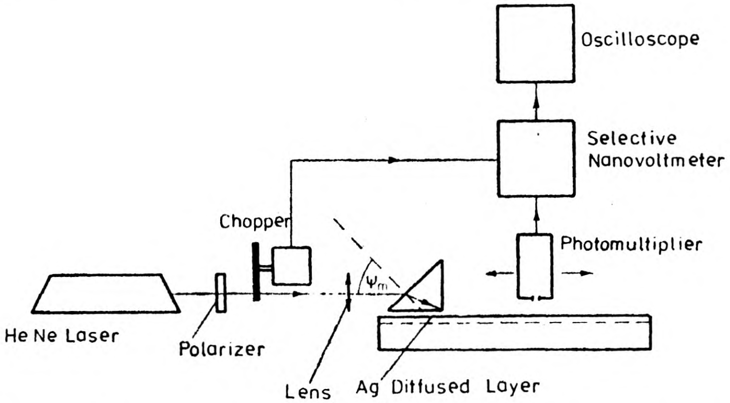
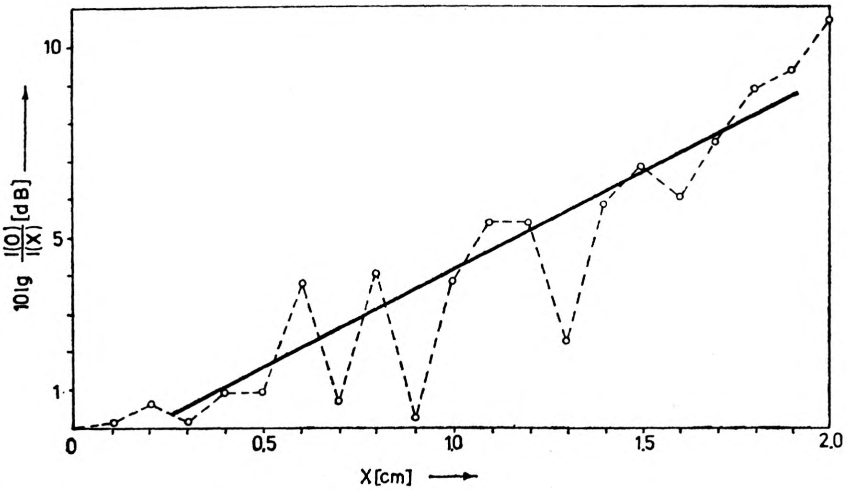
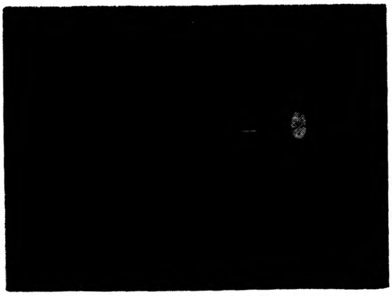


Fig. 7. Schematic diagram of attenuation measurement apparatus



a



b

Fig. 8. E_0 *T*mode attenuation in the waveguide formed by silver diffusion. Diffusion time 364 min., temperature568 K; a) graph of the measured attenuation, b) the path of the light wave propagating in the film

in dB/cm is defined by the

$$a_m = 10 \frac{1}{|x_2 - x_1|} \lg \left[\frac{I(x_1)}{I(x_2)} \right], \tag{6}$$

where $I(x)$ is the intensity of the light beam propagating along x axis of the waveguide.

Block diagram explaining the measuring method used is shown in fig. 7.

Determination accuracy of the above method is not better than ± 0.5 dB/cm. This error, mostly due to strong scattering centres, is illustrated by fig. 8.

The values of a_m have been calculated by the least-square-error method. The differences between the values of a_m obtained for each mode TE_m were not higher than the error of measuring method (cf. tab. 1).

5. Conclusions

The measurements carried out confirmed that the refraction index profile in glass diffusion waveguides can be modulated analytically by a quadratic polynomial. The applied measurement method allows to determine the complex propagation constant $\gamma_m = \beta_m + ja_m$ for the planar waveguide and its dispersion properties.

These methods being used to determine basic parameters of ion exchange process, enable the programming of the waveguide production process.

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Некоторые оптические свойства планарных световодов, полученных путем диффузии ионов серебра в стёклах

Были измерены комплексные постоянные распространения для волноводных модов света в планарном световоде, полученном путём ионной диффузии серебра в натроизвестковое стекло. Солгасование экспериментальных и теоретических характеристик создаёт возможность определить профиль козффициента преломления вдоль глубины своетовода. Полученные результаты хорошо подтверждают экспериментальны данные для профиля концентрации серебра, измеренные при использовании электронно-рентгеновского микроанализа.