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Planar diffusion glass waveguides obtained by immersing in molten KNO_3

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The paper presents the technology of obtaining planar optical waveguides in soda-lime glass by immersing in molten KNO_3 (T = 613–673 K, t = 1–25 hours). Based on the effective mode indices and the IWKB method, the analytical forms of refractive index profiles with TE and TM polarizations were determined in the waveguides. The waveguide mode attenuation measurements were made.

1. Introduction

Except for $LiNbO_3$ monocrystals, glass belongs to the materials most frequently used in the production of strip and planar optical waveguides. Such waveguides may be obtained either by ion-exchange $Ag^* \leftrightarrow Na^+$ [1], $Li^+ \leftrightarrow Na^+$ [2] or by the diffusion of Pb [3] or Tl [4] into glass. These technologies are very simple, moreover, the waveguides obtained in these ways have low attenuations (~ 1 dB/cm) and their surface refraction indices range from 1.520 to 1.605.

Diffusion glass waveguides constitute a basic constructional element of many devices in integrated optics, e.g., branching structures [5], fibre coupling structures [6], switches [7], polarizers [8], and many others.

Our paper presents the technology of producing planar optical waveguides in soda-lime glass by immersing in molten KNO_3.

2. Technology of producing diffusion glass waveguides

Planar optical waveguides were formed in soda-lime glass (microscope slides of the composition: SiO_2 – 72.11%, Al_2O_3 – 1.63%, Fe_2O_3 – 0.01%, MgO – 3.90%, CaO – 7.31%, alkaline oxides – 14.91%, the index of refraction being $n_b = 1.512$ for the He-Ne laser light, $\lambda = 0.6328$ μm) by immersion in molten KNO_3. The technological processes were carried out in a porcelain crucible, placed in a chamber oven equipped with a temperature stabilization device ± 0.5 K. The temperature was measured by the thermo-couple

Ni-NiCr drawn in a quartz shield and immersed in a bath. The bath temperature ranged from 613 to 673 K. The immersion time ranged from 1 to 25 hours.

Under the above conditions such waveguides were produced in which 1–6 TE (TM) modes could propagate.

3. Optical parameters of glass waveguides

3.1. Determination of the refractive index profile in waveguides

The effective refractive indices n_m of guided modes (TE and TM) were determined with the accuracy of ± 0.0008 by measuring the synchronous coupling angles of the above modes [9].

The obtained values of n_m were used to define the refractive index profile $n(x)$ in waveguides (x — direction is perpendicular to the surfaces of the planar waveguides) by applying the procedure followed by the IWKB method [10].

According to this method $n(x)$ appears in the form of a piecewise linear function

$$n(x) = n_k + \frac{n_{k-1}-n_k}{x_k - x_{k-1}}(x_k - x), \quad \text{for} \quad x_{k-1} < x \leqslant x_k, \tag{1}$$

where x_k represents the turning points of the modes with effective indices n_k. Having substituted (1) to a characteristic equation:

$$k_0 \int_0^{x_m} [n^2(x) - n_m^2]^{1/2} dx = \pi\left(m - \frac{3}{4}\right) + \arctan \varrho \left(\frac{n_m^2 - 1}{n_0^2 - n_m^2}\right)^{1/2}, \tag{2}$$

where

$m = 1, 2, 3, \ldots, M$ (M — number of modes propagating in a waveguide),

k_0 — light wave number in vacuum,

n_0 — refractive index on the waveguide surface,

$$\varrho = \begin{cases} 1 & \text{for TE modes,} \\ n_0^2 & \text{for TM modes,} \end{cases}$$

x_m — turning points of modes defined by the following equation,

$n(x_m) = n_m$,

the following recurrent equation for x_m was obtained:

$$x_1 = \frac{3\lambda_0}{4\pi}\left[\frac{n_0+3n_1}{2}(n_0 - n_1)\right]^{-1/2}\left[\frac{\pi}{4} + \arctan \varrho \left(\frac{n_1^2 - n_1}{n_0^2 - n_1}\right)^{1/2}\right],$$

$$x_m = x_{m-1} + \frac{3\lambda_0}{4\pi}\left[\frac{n_{m-1}+3n_m}{2}(n_{m-1} - n_m)\right]^{-1/2}$$
$$\times \left\{\pi\left(m - \frac{3}{4}\right) + \arctan \varrho \left(\frac{n_m^2 - 1}{n_0^2 - n_m^2}\right)^{1/2} - \frac{4\pi}{3\lambda_0}\sum_{k=1}^{m-1}\left(\frac{n_{k-1}+n_k}{2} + n_m\right)^{1/2}\left(\frac{x_k - x_{k-1}}{n_{k-1} - n_k}\right)\right.$$
$$\left. \times [(n_{k-1} - n_m)^{3/2} - (n_k - n_m)^{3/2}]\right\}, \tag{3}$$

for $m = 2, 3, \ldots, M$, where λ_0 — light wavelength in vacuum.

The value of n_0 indispensible for finding the first turning point x_1, was determined by making use of the fact that changes in the value of this parameter cause significant changes in the profile curvature $n(x)$. To measure the curvature we made use of the field sum of triangles with the following vertices:

$$(x_k, n_k),\ (x_{k+1}, n_{k+1}),\ (x_{k+2}, n_{k+2}),$$

$k = 0, 1, 2, \ldots, M-2$. Attempts were made to find such a value of n_0 for which the field sum would assume the least possible value.

Basing on equation (3), the turning points x_m of the modes TE and TM were found. Data sets (x_m, n_m) served to find the analytical form of $n(x)$.

For the approximation, carried out by the method of the least mean-square error, the following functions were chosen:

a linear function

$$n(x) = n_0 - \Delta n_0 \left(\frac{x}{d}\right), \quad \text{for } x < d, \tag{4}$$

$$n(x) = n_b, \quad \text{for } x \geqslant d,$$

an exponential function

$$n(x) = n_b + \Delta n_0 \left[\exp - \left(\frac{x}{d}\right)\right], \tag{5}$$

a Gaussian function

$$n(x) = n_b + \Delta n_0 \exp\left[-\left(\frac{x}{d}\right)^2\right], \tag{6}$$

a second-order polynomial function

$$n(x) = n_0 - \Delta n_0 \left[\frac{x}{d} + b\left(\frac{x}{d}\right)^2\right], \quad \text{for } x < d_1 \tag{7}$$

$$n(x) = n_b, \quad \text{for } x \geqslant d_1,$$

where d_1 is conditioned by $\left[\frac{x}{d} + b\left(\frac{x}{d}\right)\right]^2_{x=d_1} = 1,$

an erfc function

$$n(x) = n_b + \Delta n_0 \operatorname{erfc}\left(\frac{x}{d}\right), \tag{8}$$

a linear segments function

$$n(x) = n_0 + (n_w - n_0)\frac{x}{x_w}, \quad \text{for } 0 \leqslant x \leqslant x_w$$

$$n(x) = n_w + (n_b - n_w)\frac{x - x_w}{x_b - x_w}, \quad \text{for } x_w < x \leqslant x_b. \tag{9}$$

In the above formulae n_b is the bulk substrate refractive index, $\Delta n_0 = n_0 - n_b$.

The calculations were made for the waveguides produced under different technological conditions (temperature and time).

The calculations proved that the best approximation $n(x)$ in every case is obtained by means of a linear segment function (9), however, due to the way of defining the above function, it cannot be applied to describe optical properties of the whole waveguide range but only to particular cases.

In regard to the total waveguide range, the best possible approximations were obtained by applying the second-order polynomial and erfc functions; however, for the remaining approximating functions, the following relations are as a rule, fulfilled:

$$|(n_m)_{\text{measured}} - (n_m)_{\text{theoretical}}| \leqslant 0.0008.$$

For the indices n_0 and b of a parabola (7) the following mean values were assumed:

$$n_0 = 1.524, \; b = -0.270 \text{ for TE modes.}$$

$$n_0 = 1.526, \; b = -0.245 \text{ for TM modes.}$$

Standard deviations of the indices b for TE and TM modes were: 0.011 and 0.014, respectively. In the case of erfc function (8) the indices n_0 took on the same values as for a quadratic polynomial function.

The examples of the results of approximation $n(x)$ by the functions (4)–(9) for one waveguide are given in the table.

It has been proved, morover, that the changes in temperature and duration of a waveguide formation process do not cause changes in the value of the indices n_0 and b.

The relation $n_0^{TE} < n_0^{TM}$ between the values for TE and TM modes is a consequence of the noted relation between the effective refractive indices of TE and TM modes of the same orders: $n_m^{TE} < n_m^{TM}$. This situation is reverse to what would result from a characteristic mode equation. It was not influenced by the force of prism couplers clamping to a waveguide. Thus, the temporary double refraction should be related to mechanical stresses which could appear in glasses during a waveguide formation process. Similar effects have already been observed in waveguides by the ion-exchange method $Ag^+ \leftrightarrow Na^+$ [11].

3.2. Attenuation measurements

The attenuation γ of waveguide modes was measured in a system presented in a diagram (Fig. 1). A photomultiplier F was used to record the intensity changes of light, decoupled from the polished edge of a waveguide, as a function of the prism coupler distance from that edge. It is known [12] that the coupling efficiency is highly influenced by the width of the air gap which separates the prism from the waveguide; the gap width being adjusted by the clamping of both elements. In turn, the clamping force may be controlled on the basis of the picture of interference fringes visible at the prism base. The above method was used to control the efficiency of light coupling to a waveguide. The measurement method allows to determine the attenuation of waveguide modes with the accuracy of ± 0.2 dB.

The measurements were repeated many times for TE and TM modes of different orders, propagating in waveguides produced under different technological conditions.

Table. The approximation of a refractive inxed profile $n(x)$ of a light with polarization TE in a planar waveguide obtained by immersing a soda-lime glass in molten KNO_3 ($T = 673$ K, $t = 25$ hours)

m	x_m μm	n_m measured	n_m theoretical					
			quadratic polynomial function $n_0 = 1.524$ $b = -0.270$ $d = 15.9$ μm $\xi = 2.301 \cdot 10^{-7}$	erfc function $n_0 = 1.524$ $d = 21.2$ μm $\xi = 2.205 \cdot 10^{-7}$	exponential function $n_0 = 1.526$ $d = 11.5$ μm $\xi = 4.523 \cdot 10^{-7}$	Gaussian function $n_0 = 1.521$ $d = 16.5$ μm $\xi = 9.404 \cdot 10^{-7}$	linear function $n_0 = 1.523$ $d = 23.4$ μm $\xi = 7.139 \cdot 10^{-7}$	linear segments function $n_0 = 1.523$ $n_w = 1.516$ $x_w = 14.2$ μm $x_b = 31.3$ μm $\xi = 4.302 \cdot 10^{-8}$
1	4.4	1.5210	1.5212	1.5211	1.5214	1.5203	1.5208	1.5211
2	7.7	1.5194	1.5191	1.5192	1.5190	1.5192	1.5192	1.5192
3	10.1	1.5180	1.5179	1.5179	1.5177	1.5181	1.5181	1.5180
4	12.2	1.5167	1.5169	1.5169	1.5168	1.5171	1.5172	1.5168
5	14.8	1.5156	1.5158	1.5158	1.5158	1.5160	1.5160	1.5156
6	18.5	1.5148	1.5147	1.5146	1.5148	1.5145	1.5143	1.5148

$$\xi = \sum_{m=1}^{M} [(n_m)_{\text{measured}} - (n_m)_{\text{theoretical}}]^2$$

Figure 2 illustrates the dependence of the TE mode attenuation on n_m, and, in consequence, on the mode order.

Figures 3a and b present the results of investigations of the TE_1 mode attenuation being treated as a function of the KNO_3 bath temperature and substrate immersion time.

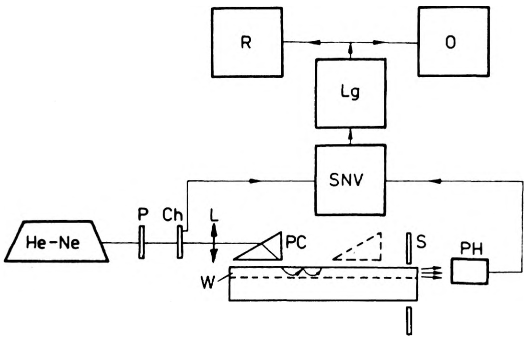

Fig. 1. Block diagram of the system for measuring the attenuation of the diffusion glass waveguide modes: *P* — polarizer, *Ch* — chopper, *L* — lens, *PC* — prism coupler, *PH* — photomultiplier, *SNV* — selective nanovoltmeter, *LG* — lg amplifier, *R* — recorder, *O* — oscilloscope, *W* — waveguide, *S* — shield

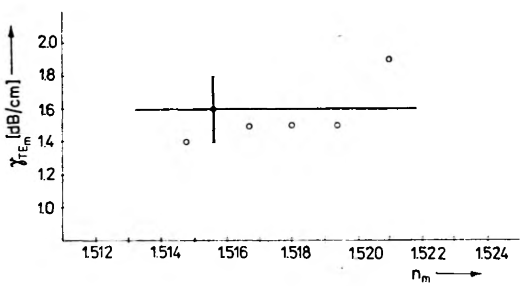

Fig. 2. Light attenuation for $\lambda = 0.6328$ μm with polarization of TE in a diffusion glass waveguide (T = 613–673 K, t = 25 hours) as n_m function

A considerable dispersion of the values may be noticed particularly well in Figs. 3 a, b. It seems that this dispersion results from the imperfections in the technological and measurement methods, as well as from the scatter of properties of soda-lime glass substrates.

In view of the above situation the following equations:

$$\gamma_{TE} = f(n)_m, \ \gamma_{TE_1} = f(T), \ \gamma_{TE_1} = f(t)$$

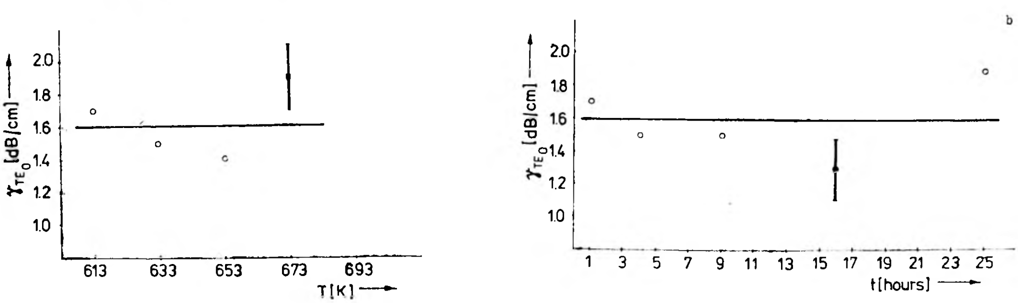

Fig. 3. Attenuation of TE_0 modes as the function of parameters of the waveguide formation process: a — temperature (t = 25 hours), b — time (T = 673 K)

had to be tested statistically. The tests, based on t-Student's distribution have showed that at the significance level $\alpha = 10\%$ γ_{TE} is almost independent of n_m, while γ_{TE_1} is almost independent of T and t.

4. Conclusions

In planar waveguides produced by dipping soda-lime glass substrates in molten KNO_3, the refractive index profile may be approximated by either a quadratic polynomial function or by an erfc function. Such waveguides are optically anisotropic which is manifested by different n_0 values of TE and TM modes: $n_0^{TE} = 1.524$, $n_0^{TM} = 1.526$. The changes in the parameters of technological processes, like temperature and time, for the waveguide production have no influence on the values of n_0. Moreover, they do not influence the waveguide mode attenuation which, irrespective of the mode order, takes on the value of about 1.6 dB/cm.

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Планарные диффузные стеклянные волноводы, полученные методом погружения в расплавленном KNO_3

В работе представлена технология изготовления планарных световодов в натроизвестковом стекле методом выдержки в расплавленном KNO_3 (T = 613-673 K, t = 1–25 часов). На основе измерений эффективных коэффициентов преломления модов и метода IWKB были определены аналитические формы профилей коэффициентов преломления света с поляризацией TE и TM в световодах. Произведены измерения затухания светловодовых модов (1,6 дБ/см).