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# Some optical properties of planar borosilicate glass waveguides formed in molten $KNO_3$ bath

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The paper presents the optical properties (refractive index profile $n(x)$, modes attenuation) of planar borosilicate (BK-7 type) glass waveguides formed in molten $KNO_3$ bath. The results of thermal stability investigations of these optical guides parameters are also presented; the properties of BK-7 glass waveguides are compared with the properties of sode-lime glass waveguides formed in molten nitrates baths: $AgNO_3$ and $KNO_3$.

## 1. Introduction

One of the most widely used methods for planar optical waveguides production is the one based on ion-exchange and diffusion process in glasses; waveguides are produced by dipping alkaline glass substrate plates in molten nitrates baths, such as $AgNO_3$ [1], $AgNO_3 + NaNO_3$ [2], $CsNO_3$ [3], $TlNO_3 + KNO_3$ [4]. These technologies are characterized by simplicity, satisfactory repeatability and accessibility of the main raw material (glass plates).

For a fixed type of substrate glass, the magnitude of refractive index value changes depends on the kind of bath used. It is also possible to modify the refractive index profile by using an external electric field [5]. The waveguides obtained in these ways have low mode attenuation ($\sim$1 dB/cm). Basing on the literature [3, 6] one should note that few investigations have been concerned with the properties of the glass waveguides formed in the bath of molten $KNO_3$.

In our previous paper [7] we have presented the optical properties of the soda-lime glass waveguides produced by dipping in molten $KNO_3$. In this paper we describe properties of the borosilicate (BK-7 type) glass waveguides formed in the same kind of bath. The same technological and scientific instruments, as previously [7], have been used for production and investigation of these waveguides. The values of optical waveguides parameters have been determined for He–Ne laser light ($\lambda = 0.6328$ μm).

## 2. Formation of planar glass waveguides

Planar optical waveguides were formed by immersing BK-7 glass plates (the composition being [8]: $SiO_2$ – 69.58 %, $B_2O_3$ – 9.91 %, BaO – 2.54 %, $Na_2O$ – 8.44 %, $K_2O$ – 8.37 %, $Al_2O_3$ – 0.04 %, $Fe_2O_3$ – 0.01 %, MgO – 0.07 %, CaO – 0.07 %, $H_2O$ – 0.06 %, Cl – 0.06 %, $SO_3$ – 0.08 %, $As_2O_3$ – 0.09 %, $AsO_5$ – 0.22 % in molten $KNO_3$ 99.8 (percent pure).

The bath temperature ranged within 613–673 K and the immersion time ranged from several minutes to 25 hours. Under such conditions waveguides were produced in which 1–6 modes could propagate.

## 3. Optical properties of waveguides

### 3.1. The determination of a refractive index profile in waveguides

During investigations of mode lines in formed waveguides, it was observed that for modes of orders $m = 1$ or $m = 2$ and higher (as well for TE modes as for TM ones) the values of their effective indices were smaller than the value of glass substrate index of refraction (this value being $1.520 \pm 0.003$* has been determined from the measurements of Brewster angle). It seems that technological process (i.e. dipping of a BK-7 glass plate in molten $KNO_3$) leads to formation of local minimum of refractive index value $n_b$. This minimum "isolates" the region in which light can propagate from the substrate.

The refractive index profiles $n(x)$ in the examined waveguides were calculated basing on the procedure followed by I.W.K.B. method [7]; the profiles $n(x)$ were defined by data sets $(x_m, n_m^{ef})^{TE(M)}$ ($x_m$ – the turning point of mode). Next, the values $n_b$ were estimated using the following method (Fig. 1).

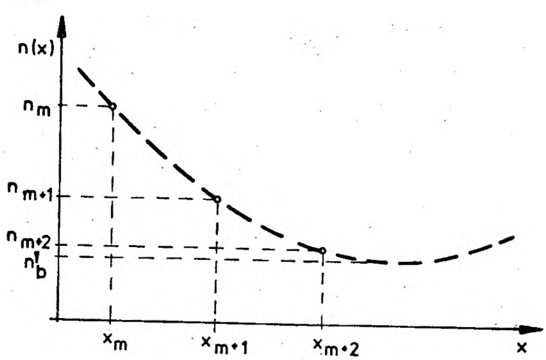


Fig. 1. Determination of $n_b^{TE(M)}$

* In the paper, standard deviations were presented as the errors of determined optical parameter values.

The minimal values of parabolic function defined by data sets $(x_m, n_m^{ef})^{TE(M}$ were determined; the values $x_m$ and $n_m^{ef}$ concerned three modes of the highest order. To test the correctness of the method, it was used to determine the refractive index value $n_b$ of soda-lime glass plate (results of mode patterns investigations [7] in waveguides, in this type of glass, produced also in molten $KNO_3$ were used). The obtained value was $n_b = 1.5142 \pm 0.0004$, while that determined from the measurements of Brewster angle was $n_b = 1.512 \pm 0.002$. In the case of BK-7 glass waveguides, by the described method the following mean values of $n_b$ parameter were obtained: $n_b{}^{TE} = 1.5061 \pm 0.0025$ and $n_b{}^{TM} = 1.5036 \pm 0.0019$ (in all the waveguides examined $n_b^{TE} > n_b^{TM}$). One should not exclude the fact that the values of parameter $n_b^{TE(M)}$ can vary together with the changing technological conditions ($T$ — bath temperature, $t$ — duration time) in which optical waveguides have been formed. The data which were at our disposal were, however, too scarce to enable the definition of the character of such hypothetical changes. Basing on the sets of values $(x_m, n_m^{ef})^{TE(M)}$ and $n_b{}^{TE(M)}$ and using the least mean-square error method, the analytical form of $n(x)$ profile approximating function in investigated waveguides was calculated. For the approximation the linear, parabolic, Gaussian, erfc and exponential functions were chosen. The calculations made for the waveguides produced in different technological conditions have proved that in the waveguides regions limited by turning points of propagating modes the best approximation $n(x)$ is in every case obtained by means of a parabolic function

$$n(x) = n_b = \Delta n_s[(x/d) + b(x/d)^2] \tag{1}$$

where $\Delta n_s = n_s - n_b$,

$n_s$ — refractive index on a waveguide surface,

$b, d - n(x)$ function parameters.

The examples of approximation $n(x)$ results for one of the waveguides are shown in Table 1.

It has been shown that the changes in temperature and the duration time of a waveguide formation process do not cause significant changes in the values of $n_s$ and $b$ indices. The indices $n_s$ and $b$ of a parabola (1) assumed the following mean values:

$$n_s^{TE} = 1.524; \quad b^{TE} = -0.4038 \pm 0.0013;$$

$$n_s^{TM} = 1.526; \quad b^{TM} = -0.6030 \pm 0.0053.$$

The relation between the values $n_s$ of TE and TM modes ($n_s^{TM} > n_s^{TE}$) results from the relation between the effective refractive indices of TE and TM modes of the same orders: $n_m^{efTM} > n_m^{efTE}$ being thus reverse of what would result from a characteristic mode equation.

The temporary double refraction should be related to mechanical stresses

Table 1. The approximation of a refractive index profile $n(x)$ of light with polarization TE in a planar BK-7 glass waveguide (molten $KNO_3$ bath, $T = 673$ K, $t = 25$ hours)

| $m$ | $x_m$ [μm] | $n_m^{ef}$ measured | $n_m^{ef}$ theoretical | | | | |
|---|---|---|---|---|---|---|---|
| | | | Parabolic function $n_s = 1.5240$ $b = -0.4005$ $d = 19.8$ [μm] $\sigma = 5.550 \cdot 10^{-8}$ | Erfc function $n_s = 1.5228$ $d = 33.8$ [μm] $\sigma = 4.617 \cdot 10^{7}$ | Linear function $n_s = 1.5224$ $d = 33.8$ [μm] $\sigma = 7.948 \cdot 10^{7}$ | Exponential function $n_s = 1.5234$ $d = 22.0$ [μm] $\sigma = 1.916 \cdot 10^{-7}$ | Gaussian function $n_s = 1.5206$ $d = 23.5$ [μm] $\sigma = 1.997 \cdot 10^{-6}$ |
| 0 | 4.104 | 1.5214 | 1.52136 | 1.52106 | 1.52089 | 1.52112 | 1.52029 |
| 1 | 7.287 | 1.5196 | 1.51963 | 1.51973 | 1.51972 | 1.51962 | 1.51963 |
| 2 | 10.122 | 1.5182 | 1.51833 | 1.51860 | 1.51868 | 1.51845 | 1.51881 |
| 3 | 13.701 | 1.5172 | 1.51702 | 1.51725 | 1.51737 | 1.51718 | 1.51755 |
| 4 | 16.073 | 1.5163 | 1.51635 | 1.51641 | 1.51650 | 1.51645 | 1.51664 |
| 5 | 19.799 | 1.5156 | 1.51562 | 1.51521 | 1.51513 | 1.51544 | 1.51521 |

$\sigma = \sum_m [(n_m^{ef})\ \text{measured} - (n_m^{ef})\ \text{theoretical}]^2$

which could appear in glasses during the waveguide formation process. Similar effects have already been observed in soda-lime glass waveguides formed in the baths: $AgNO_3 + NaNO_3$ [9] and $KNO_3$ [7].

### 3.2. Attenuation measurements

The values of mode attenuations $\alpha$ in BK-7 glass waveguides produced in different technological conditions were determined, for TE and TM modes of different orders. The results were similar to these obtained for waveguides produced in soda-lime glass [7]. It has been found that $\alpha$ takes a constant value of about 1 dB/cm regardless of light polarization, mode order and technological process parameters values.

## 4. Comparative thermal stability investigations of optical waveguides parameters

The temperature-induced changes of the following waveguide optical parameters were investigated:

— number of supported modes,

— refractive index profile $n(x)$,

— $TE_0$ mode attenuation.

For the comparative reasons three waveguides, formed in different types of glasses or kinds of baths, were examined:

— sample 1 – BK-7 glass waveguide produced in molten $KNO_3$ bath ($T = 673$ K, $t = 4$ hours),

— sample 2 – soda-lime glass waveguide produced in molten $KNO_3$ bath ($T = 673$ K, $t = 4$ hours),

— sample 3 – soda-lime glass waveguide produced in molten $AgNO_3$ bath ($T = 523$ K, $t = 15$ minutes).

First of all the above mentioned parameters of the investigated waveguides were determined. Then the guides were annealed in air atmosphere. The annealing process proceeded at stages, each testing for 5 hours. The annealing temperature ranging within 373–723 K was changed at every 50 K. After each stage of annealing was completed, the mentioned waveguide parameters were determined again.

The changes in numbers of waveguide mode are shown in Table 2, whereas those of the refractive index profiles $n(x)$ are presented in Fig. 2 (the results shown in Fig. 2 concern profiles $n(x)$ for TE polarized light; the changes for TM polarized light have a similar nature).

At later stages of annealing (the highest temperatures) all the investigated waveguides, though to different degree, suffered destruction; there were difficulties in light coupling (by prisms) into the waveguides and the mode spectra were distorted.

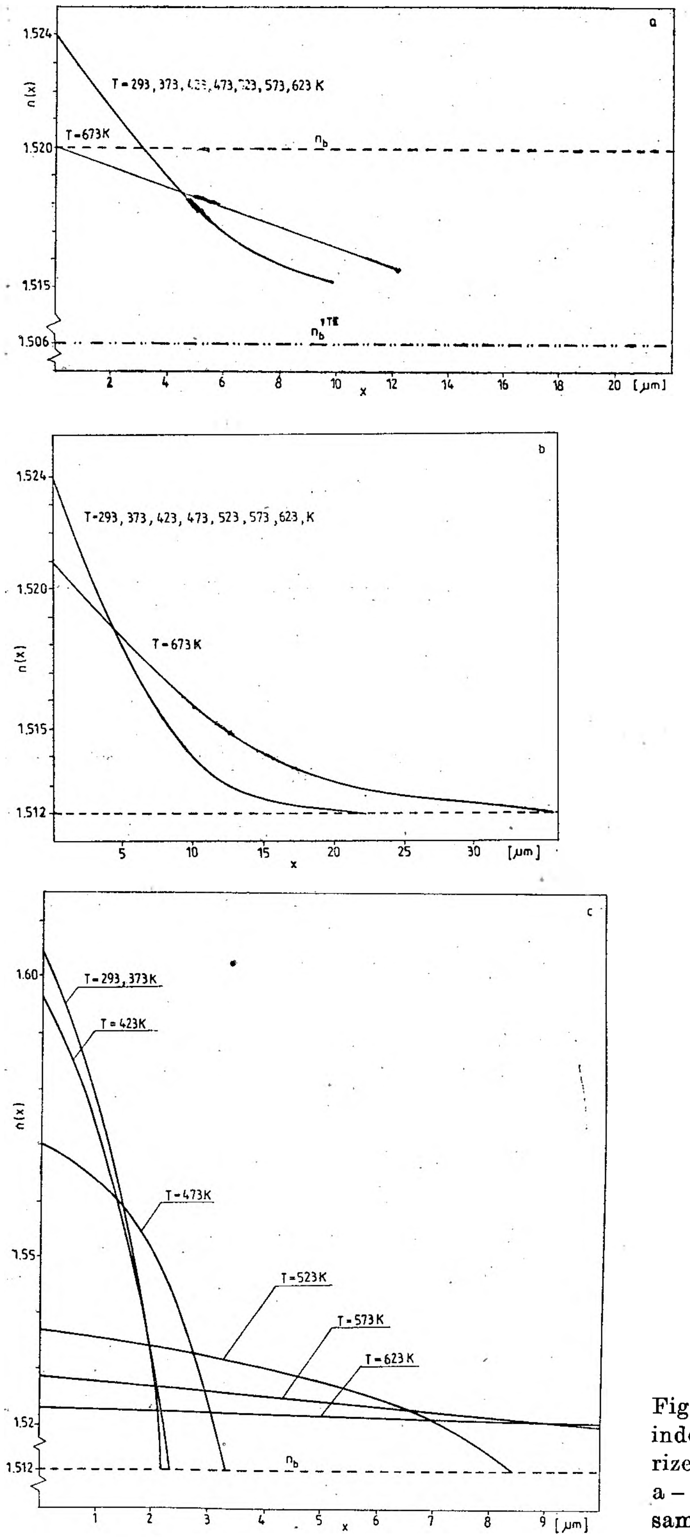


Fig. 2. The changes in refractive index profiles $n(x)$ (for TE polarized light) caused by annealing: a – sample 1, b – sample 2, c – sample 3

When the annealing stage at 723 K was completed it was impossible to couple light into the soda-lime glass waveguide formed in molten $KNO_3$ bath.

Table 2. The changes in number of waveguide modes caused by annealing

| Stages of annealing process (temperature, K) | TE modes | | | TM modes | | |
|---|---|---|---|---|---|---|
| | Sample 1 | Sample 2 | Sample 3 | Sample 1 | Sample 2 | Sample 3 |
| Before annealing | 3 | 3 | 3 | 3 | 3 | 3 |
| 373 | 3 | 3 | 3 | 3 | 3 | 3 |
| 423 | 3 | 3 | 3 | 3 | 3 | 3 |
| 473 | 3 | 3 | 3 | 3 | 3 | 3 |
| 523 | 3 | 3 | 5 | 3 | 3 | 5 |
| 573 | 3 | 3 | 7 | 3 | 3 | 7 |
| 623 | 3 | 3 | 9 | 3 | 4 | 9 |
| 673 | 3 | 4 | — | 4 | 4 | — |

In the case of BK-7 glass waveguide at 723 K the pattern of distorted modes was observed even for waveguides annealed, whereas the annealing of the waveguide formed in molten $AgNO_3$ bath at 673 K brought its mode spectrum to distortion. Having completed the next annealing stage, it was impossible to couple light into this guide.

The mode attenuation changes caused by the annealing process are shown in Fig. 3. It is seen for the waveguides formed in molten $KNO_3$ bath that the values of $\alpha$ altered distinctly (they decreased by $\Delta\alpha \sim (0.6\text{–}0.7)$ dB/cm with respect to their original values) only after these optical guides had been annealed at 673 K. During the annealing process the surface of the waveguide formed in molten $AgNO_3$ bath covered with metallic thin film, formed probably by silver atoms (ion) diffusing from a bulk of the sample. Due to the presence of this film the value $\alpha$ increased ($\alpha \sim (6\text{–}7)$ dB/cm). After this film was removed by rubbing with cotton wool, the value of $\alpha$ decreased distinctly (the values of $\alpha$ shown in Fig. 3 were determined after the metallic film had been removed).

## 5. Conclusions

The paper presents the properties of the BK-7 glass waveguides formed in molten $KNO_3$ bath in a complex way. The mentioned optical guides are characterized by:

– the existence of the minimum value of local refractive index,

– temporary double refraction (manifested by different values of $n_s$ of TE and TM modes),

– low mode attenuations ($\alpha \sim 1$ dB/cm),

– the changes of refractive index values (compared with that for the

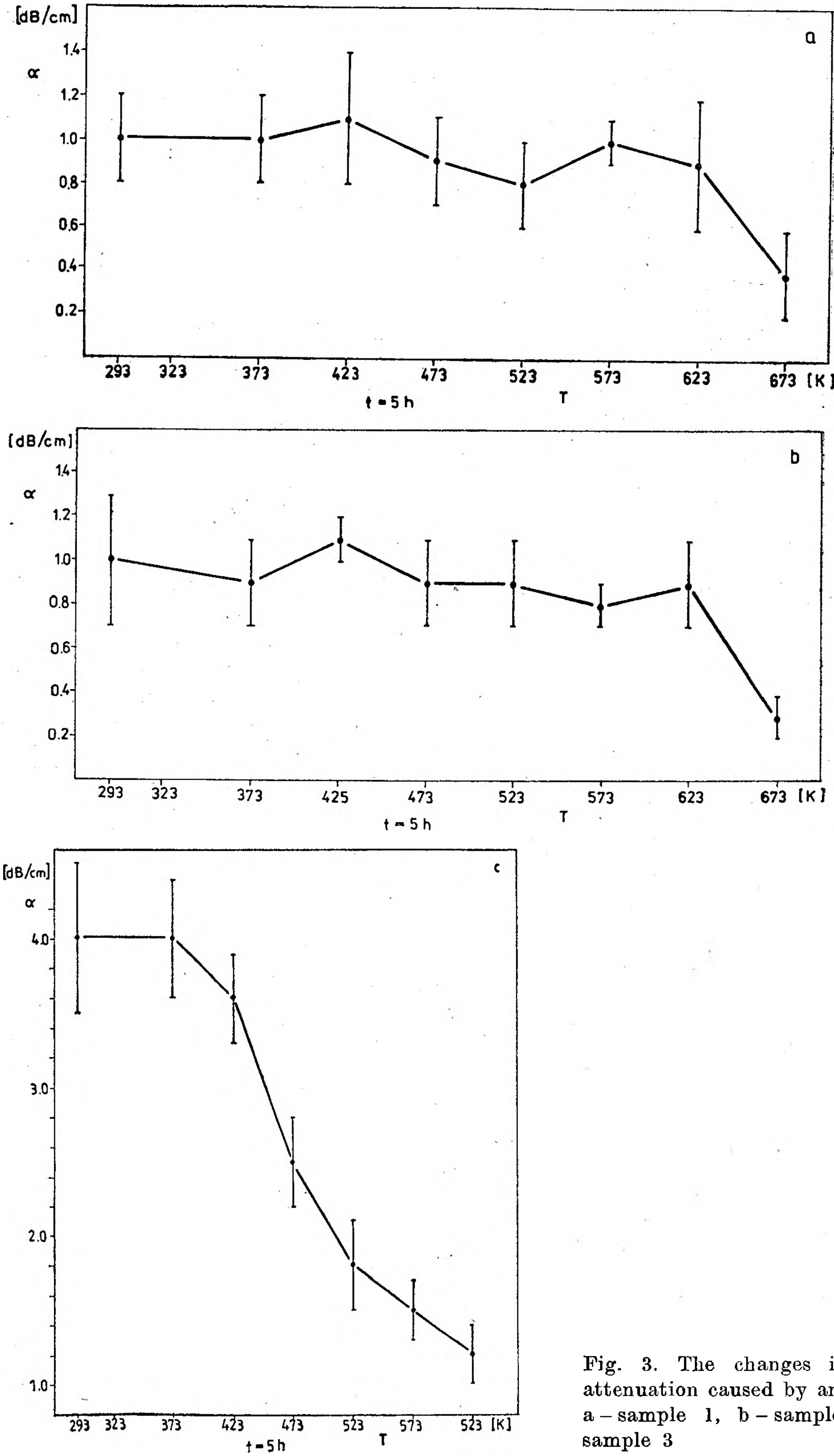


Fig. 3. The changes in mode attenuation caused by annealing: a – sample 1, b – sample 2, c – sample 3

substrate) being: ~0.004 and ~0.006 for TE and TM polarized light, respectively.

The changes in technological parameters of waveguide production do not affect the values of $n_s$. Moreover, they do not influence the attenuation of the waveguide modes.

A considerable thermal resistance of BK-7 glass waveguides should be emphasized, particularly in comparison with the properties of optical soda-lime glass waveguides formed in molten $AgNO_3$ bath.

## References


[1] Finak J., Jerominek H., Żelechower M., Optica Applicata **11** (1981), 61.
[2] Stewart G., Laybourn P. J. R., IEEE J. Quant. Electron. **QE-14** (1978), 930.
[3] Neuman V., Parriaux O., Walpita L. M., Electron Lett. **15** (1979), 704.
[4] Kawanishi H., Suematsu Y., The Trans. of the IECE Japan, **E 60** (1977), 231.
[5] Chartier G. H., Jaussaud P., De Oliveira A. D., Parriaux O., Electron. Lett. **14** (1978), 132.
[6] Giallorenzi T. G., West E. J., Kirk R., Ginther R., Andrews R. A., Appl. Opt. **12** (1973), 1240.
[7] Finak J., Jerominek H., Opilski Z., Wojtala K., Optica Applicata **12** (1982), 11.
[8] Płoński J., *Technologia szkla optycznego*, Arkady, Warszawa 1962 (in Polish)


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### Некоторые оптические свойства планарных световодов в боросиликатном стекле, образуемых в ванне сплавленного $KHO_3$

В работе обсуждены оптические свойства (вид профиля коэффициента преломления света $n(x)$, затухание) планарных световодов в боросиликатном стекле БС-7, образуемых в ванне сплавленного $KNO_3$. Представлены, кроме того, результаты исследований термической устойчивости оптических параметров тех же световодов; их свойства сравнены со свойствами световодов в нитриевокальциевом стекле, созданных в ванне сплавленных нитратов: $AgNO_3$ и $KNO_3$.

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