

Planar optical waveguides on glasses and glassceramic materials

Leonid B. Glebov, Nikolai V. Nikonorov, Gurii T. Petrovskii

All-Union Research Center "S.I. Vavilov State Optical Institute"
199034, Leningrad, USSR

ABSTRACT

New possibilities of glasses and glassceramic materials for integrated optics have been shown. Formation questions of planar waveguides by the ion exchange method on the basis of transmitting, controlling and recording glassy materials have been considered. Examples of various controlled waveguide elements on the basis active glasses are presented.

1. INTRODUCTION

Glass is one of the most promising materials for designing integrated optic devices. A low-temperature ion exchange technique is a simple and commonly used method for obtaining waveguides based on glasses assuring of high quality glass surface preservation and low losses in waveguides. To date there are a lot of original papers and reviews on both optical properties of waveguides based on glasses and ion exchange technology to produce them^{1,2}. As a general rule, commercially available glasses such as: BK-7, TiF, BGG-21, window glass, microscopic glass^{1,2}, are employed as substrates. Specially synthesized glasses such as alkaline silicate, alkaline borosilicate, alkaline aluminosilicate are very seldom used to form waveguide layers by ion exchange. This restricts optical characteristics variability of waveguides since industrially prepared glasses had been designed for purposes unrelated to integrated optics. In order to make waveguides with desired performances it is essential to design novel special-purpose glasses with various glass-forming matrices that could provide adequate characteristics through use of an optical processing technique. Optical substances mentioned above fall into category of passive (i.e. transmitting the light energy) glasses. It should be noted that there exists category of active glasses which can control light fluxes (for example, electrooptical, magneto-optical and electrochromic glasses) or which properties can be changed under the action of light (for example, laser, photochromic and polychromic glasses). Some of glasses (for example, laser glasses) can compete with crystalline substances and semiconductors in their active characteristics and can even be superior to those in such properties as: homogeneity, processability, reproducibility of parameters and low losses. However, only rare publications are available that are focused on formation of waveguides using active glasses. Our efforts have resulted in extending the categories of both passive and active glasses that could be used for the planar waveguides fabrication by the ion exchange technique.

2. ION DIFFUSANTS

Ag^+ and Tl^+ ions as well as such alkali metal ions Li^+ , Na^+ , K^+ , Rb^+ , Cs^+ are widely used as diffusants while forming waveguide layers. The Ag^+ and Tl^+ -ion exchange waveguides have the highest increase in the refractive index ($\Delta n \sim 0.1$). However, they have a number of disadvantages limiting their use in integrated optics. Among these are the low thermal and photo-stability of the Ag^+ -waveguide and high toxicity of the Tl^+ -waveguide production. Alkali metal ions are most promising in view of commercial waveguide production. The use of these ions permits one to make waveguides with low losses (about 0.1 dB/cm) and improve physical and chemical properties of a glass. For example, samples of glass treated in KNO_3 -melt ($\text{Na}_{\text{glass}}^+ \rightleftharpoons \text{K}_{\text{melt}}^+$) have the extra mechanical, thermal and light strength. In our work we have used alkali metal ions for obtaining planar waveguides.

3. MECHANISMS OF FORMING THE WAVEGUIDE REFRACTIVE INDEX

An increase in the refractive index in a glass surface layer Δn as well as forming a waveguide while the low-temperature ion exchange are governed by a couple of mechanisms:

1. glass composition change (the refractive index change can be modelled as $\Delta n^c = c \cdot I^c$, where c - diffusant ions concentration, I^c - the structural refractive index increment determined by the difference in exchanging ions specific refractions);
2. diffusion stresses development and relaxation (the refractive index change can be modelled as $\Delta n^t = c \cdot I^t$, where I^t - the tensor refractive index increment determined by photoelastic action of stresses). The stresses arise as a result of ions exchange with different radiuses.

The diffusion stresses can be divided into three groups:

1. Stresses associated with a difference between the thermal expansion coefficients of an ion exchange layer and substrate. Those contribution into the total refractive index increment is small ($\Delta n \sim 10^{-5}$) and may be, therefore, neglected.
2. Macro stresses resulting from interaction of an ion exchange layer seeking to increase its volume and a substrate unaffected by exchange. These stresses are anisotropic and govern both the anisotropic refractive index increment (Δn_{mac}) and birefringence ($\delta n = n^{\text{TM}} - n^{\text{TE}}$).
3. Micro stresses stemming from interaction of diffusant ions with their immediate surroundings. These stresses control the isotropic increment (Δn_{mic}) of the refractive index.

The contribution of mechanisms listed above depends on: exchanging ion kinds, glass composition and structure, and ion exchange process temperature and duration. Let us consider some examples Fig.1 shows variations of the refractive index with the K_2O concentration in an ion exchange layer ($\text{Na}_{\text{g}}^+ \rightleftharpoons \text{K}_{\text{m}}^+$ exchange, glass type K-8). A change in the chemical composition results in

decreasing the refractive index (curve 1, I^s - negative). Compression stresses cause the refractive index to rise (curves 2 and 3, I^t - positive). As a result, the total refractive index change (summation curve 5, $I^s + I^t > 0$) is positive. The same behavior is observed while exchanging $Li_g^+ \leftrightarrow K_m^+$. Fig.2 indicates calculated refractive index profiles determined by variation in the composition (curve 1) and by diffusion stresses (curve 2 and 3). The total refractive index change is positive for both TE- and TM-polarization modes (curves 4 and 5). So, a waveguide layer forming is dominated by diffusion stresses while the low-temperature ion exchange like $Li_g^+, Na_g^+ \leftrightarrow K_m^+$. In exchanging $Na_g^+, K_g^+ \leftrightarrow Rb_m^+, Cs_m^+$ the structural and tensor increments are positive. In this process, the chemical composition change plays a leading role in the refractive index increase.

4. FEATURES OF ION EXCHANGE WAVEGUIDES MADE USING A PHOTOELASTICITY EFFECT

A relationship between chemical composition change and refractive index in the process of low-temperature ion exchange is in large part dictated by diffusion stresses and their relaxation, as well. The diffusion stress relaxation process results in non-monotonic forms of interrelations between optical, mechanical and concentration changes in glasses (see Fig.3). The stress relaxation in glass surface layer entails forming a non-monotonic stress profile and refractive index. In such a manner it is possible to make a buried waveguide using the one-step ion exchange due to the relaxation process. The buried waveguide characteristics can be controlled by the variation of ion exchange temperature or duration. Fig.4 presents the monotonic and non-monotonic refractive index profiles for waveguides on silicate glass K-8 and glassceramic ($Li_g^+, Na_g^+ \leftrightarrow K_m^+$) at varied duration of ion exchange.

The K^+ -ion-exchange waveguides on glasses have the high birefringence $\delta n = B \cdot \sigma \approx 30 \cdot 10^{-4}$ (B - optical factor of stresses). Using glasses with the high B -value and controlling the σ -value at the early ion exchange stage one can make an anisotropic layer on the glass surface in which the refractive index for TM-polarization (n^{TM}) is more than the one for the substrate (n_s). Such a layer has waveguide properties. The TE-polarization refractive index (n^{TE}) is close to the critical one ($n^{TE} \approx n_s$) and waveguide modes does not propagate in this case. Fig.5 gives examples of polarization waveguide selectors using this effect. We have used both titanium-germanate ($B=4.7 \cdot 10^{12} \text{ Pa}^{-1}$) and niobium-germanium-silicate ($B=3.5 \cdot 10^{12} \text{ Pa}^{-1}$) glasses. Such kinds of waveguide polarizers have the high selection efficiency (about 100 dB/cm). So, employing a photoelasticity effect during the ion exchange one can obtain original waveguide structures such as buried waveguides and polarization filters.

5. TRANSMITTING GLASSES FOR ION EXCHANGE WAVEGUIDES

Challenges for light energy transmitting glasses to be aimed at ion exchange waveguides can be formulated as follows. The glasses are bound to combine good optical and spectral properties (such as low scattering and absorption, variability of optical constants over the wide spectral range) with adequate ion exchange capabilities (high interdiffusivities of alkaline ions). Besides, the glasses should have the high mechanical, thermal, optical strength and chemical stability. We have developed such ion exchange waveguide glasses as: borosilicate, zirconium-silicate, zirconium-germanium-silicate, zirconium-niobium-silicate, niobium-germanium-silicate, silicon-phosphate, germanium-phosphate, niobium-phosphate, magnesium-phosphate, titanium-germanate, alumino-germanate. The glass and waveguide characteristics are tabulated in Table 1. A wide range of glasses allows waveguides with various performances to be achievable. As for example, waveguides on zirconium-silicate glasses and glassceramics are characterized by their high mechanical and thermal strength. Silicon-phosphate glasses and waveguides are distinguished for their athermal properties. Germanium-phosphate glasses are high values of interdiffusivities (about $10^{-5} \text{ cm}^2 \cdot \text{s}^{-1}$). Titanium-germanate glasses and waveguides feature the high refractive indices ($n = 1.77$).

6. ACTIVE GLASSES FOR ION EXCHANGE WAVEGUIDES

We have made planar waveguides on such active glasses as : laser glass (neodymium silicate and phosphate ones), photochromic (both homogeneous and heterogeneous ones containing microcrystals of AgCl, AgBr and CuCl), polychromic (with microcrystals of NaF and Ag-NaBr), electrochromic (niobium-phosphate ones), magneto-optical, electro-optical (with microcrystals of NaNbO_3), and the ones containing semiconductor microcrystals CdS-CdSe. The glass and waveguide characteristics are tabulated in Table 2. Active properties of waveguides resemble those for three-dimensional samples of starting glasses. Waveguides on these glasses can control and record light fluxes. For instance, we have obtained amplification in waveguides on laser glasses at lamp pumping. Photo- or electroinduced light absorption effects have been observed in waveguides on photochromic and electrochromic glasses. The light absorption photoinduced in photochromic waveguides may be both reversible or irreversible. It is possible to register light fluxes in the waveguides on photochromic or polychromic glasses and in this way, to record amplitude or phase holograms. We will consider a few examples of optical waveguide elements based on photosensitive glasses.

7. EXAMPLES OF WAVEGUIDE ELEMENTS ON PHOTSENSITIVE GLASSES

Space and polarization waveguide mode selectors are demanded for solving various problems of integrated optics. Such kinds of selectors can be designed basing on photochromic glasses (either homogeneous or heterogeneous) and controlled by the external or waveguide radiation. Fig.6a and Fig.6b demonstrate a space waveguide mode selectors controlled by the

external radiation. An absorption profile may be formed using some special approaches such as waveguide in depth distribution of photosensitivity centers and selection of an activating radiation wavelength. Since modes in an graded index optical waveguide propagate at different levels they will have losses induced according to the absorption profile. By this means selection of waveguide modes may be performed. The selection efficiencies on excitation of different mode numbers are shown on Fig.6c. The polarization selection can be carried out in an analogous way. To do this, a waveguide with the high birefringence has to be created (see Fig.7).

The both space and polarization selectors can be obtained through using waveguide radiation. In this case the absorption profile is formed by activating radiation of the waveguide. To illustrate, the activating radiation of a single mode ($N=1$) creates an absorbing negative (see Fig.8a) or positive (see Fig.8b) mask. The mask absorption profile is in agreement with the field profile of the mode being excited.

Attenuation of the rest of modes ($N=0$, $N=2$) depends on the degree of overlapping of their fields with the absorbing mask profile. In such a manner a space selection can be obtained. Fig.8c and Fig.8d show the selection efficiency for different modes when forming negative and positive masks. Polarization selectors can be made in a similar way (see Fig.9a,9b). In this case the selection efficiency rises with a birefringence increase (see Fig.9c).

8. CONCLUSIONS

Waveguides based on glasses and glassceramic materials have a great variety of optical, spectral, thermal, mechanical, and active properties, as well. Such waveguides can be used successively in integrated optics are competitive with waveguides on crystals. In this context, the development of glass compositions specially designed for integrated optics can become one of most urgent directions of material research efforts. An understanding of the refractive index forming mechanisms during the low-temperature ion exchange permits one to formulate requirements to be placed upon such materials.

7. REFERENCES

1. T. Findakly, "Glass Waveguides by Ion Exchange: A Review", Opt. Eng., vol.24, №2, pp.244-250, 1985.
2. R.V. Ramaswamy, R. Srivastava, "Ion-Exchanged Glass Waveguides: A Review", IEEE, J. Lightwave Tech., vol.6, №6, pp.984-1002, 1988.

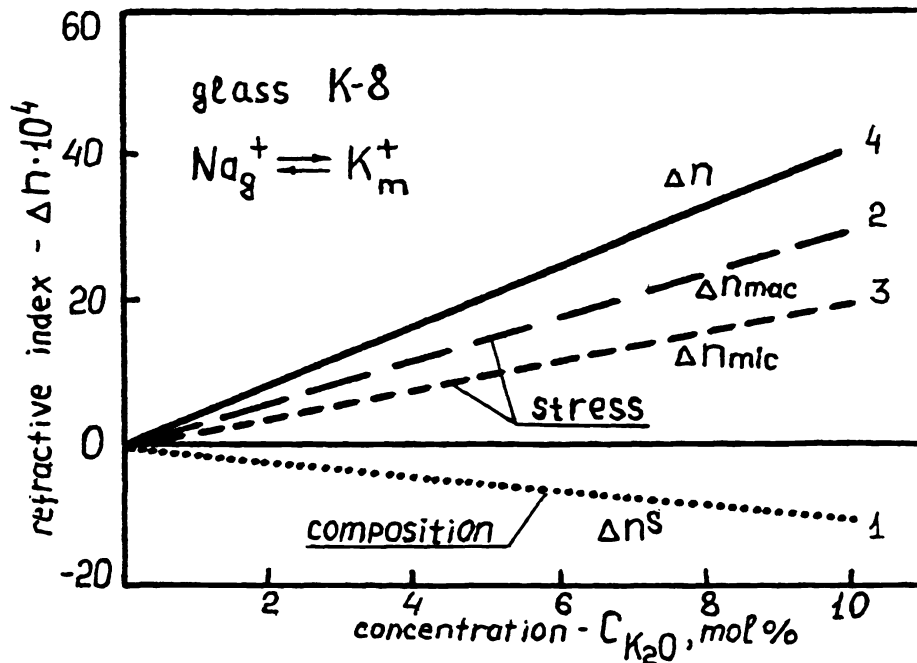


Fig. 1. Calculated variation of the refractive index as a function of concentration K_2O : 1 - influence of composition, 2 - influence of macrostress, 3 - influence microstress, 4 - summable curve.

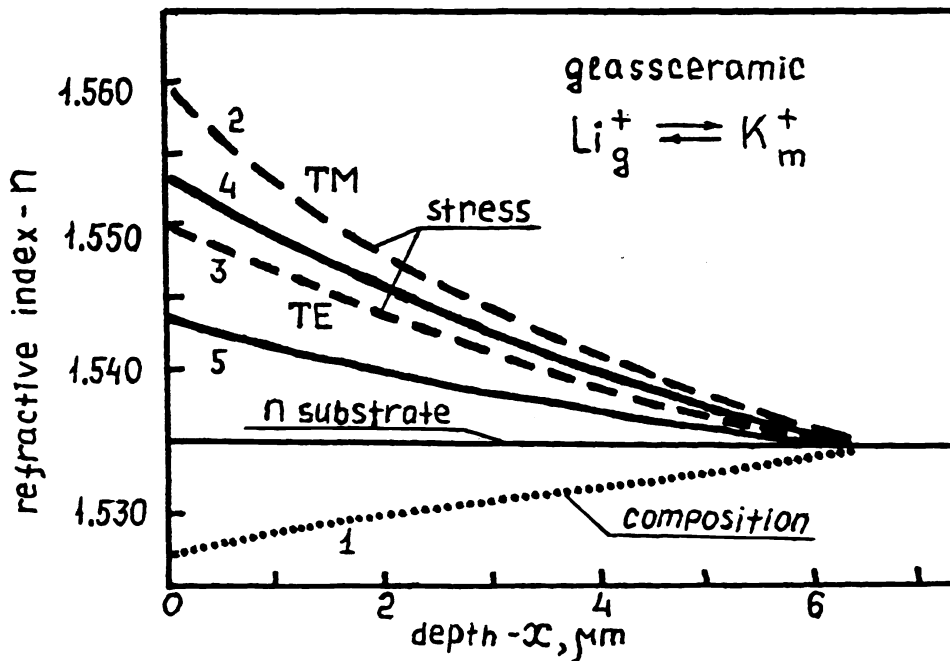


Fig. 2. Calculated refractive index profile: 1 - influence of composition, 2,3 - influence of macrostress (TM - and TE - polarization of light), 4,5 - summable curves - 1 and 2, - 1 and 3.

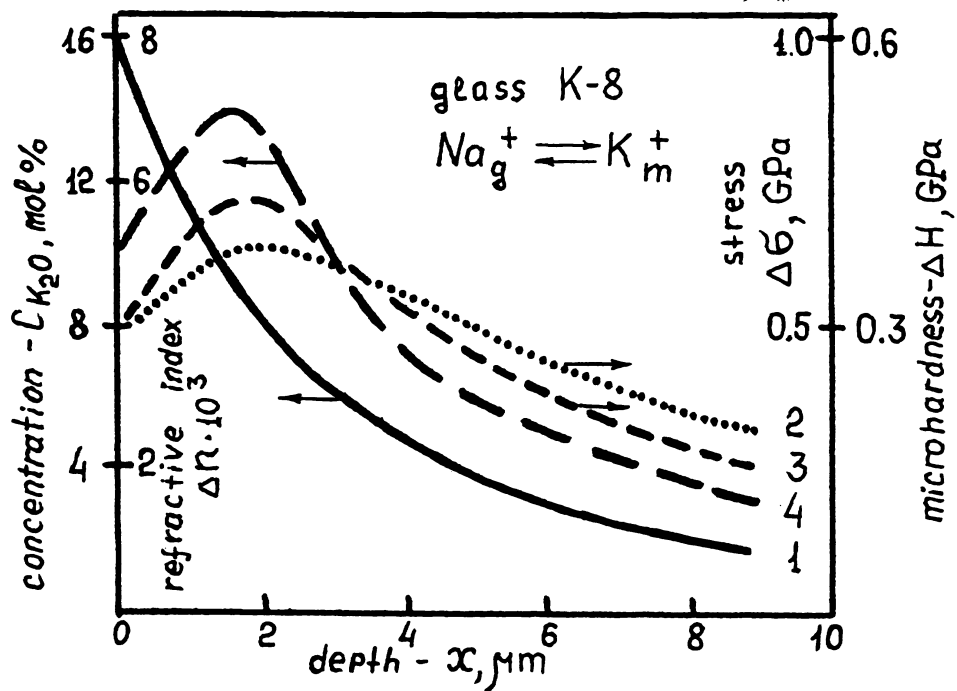


Fig. 3. Profiles of concentration K_2O (1), stress (2), microhardness (3) and refractive index (4).

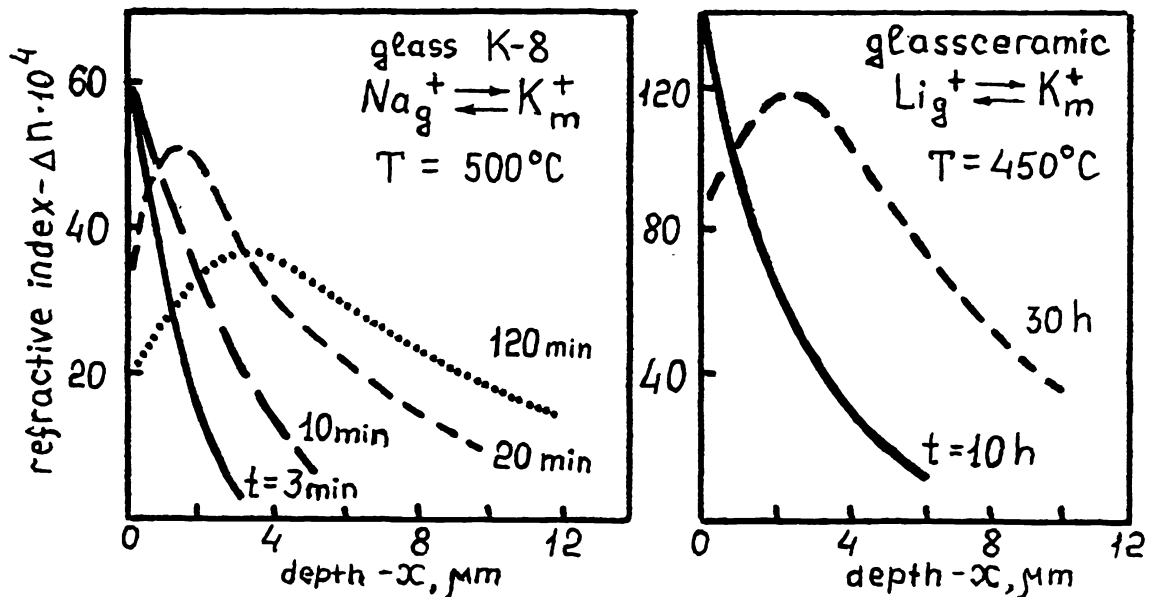


Fig. 4. Refractive index profiles of ion-exchanged glass and glassceramic waveguides for various times.

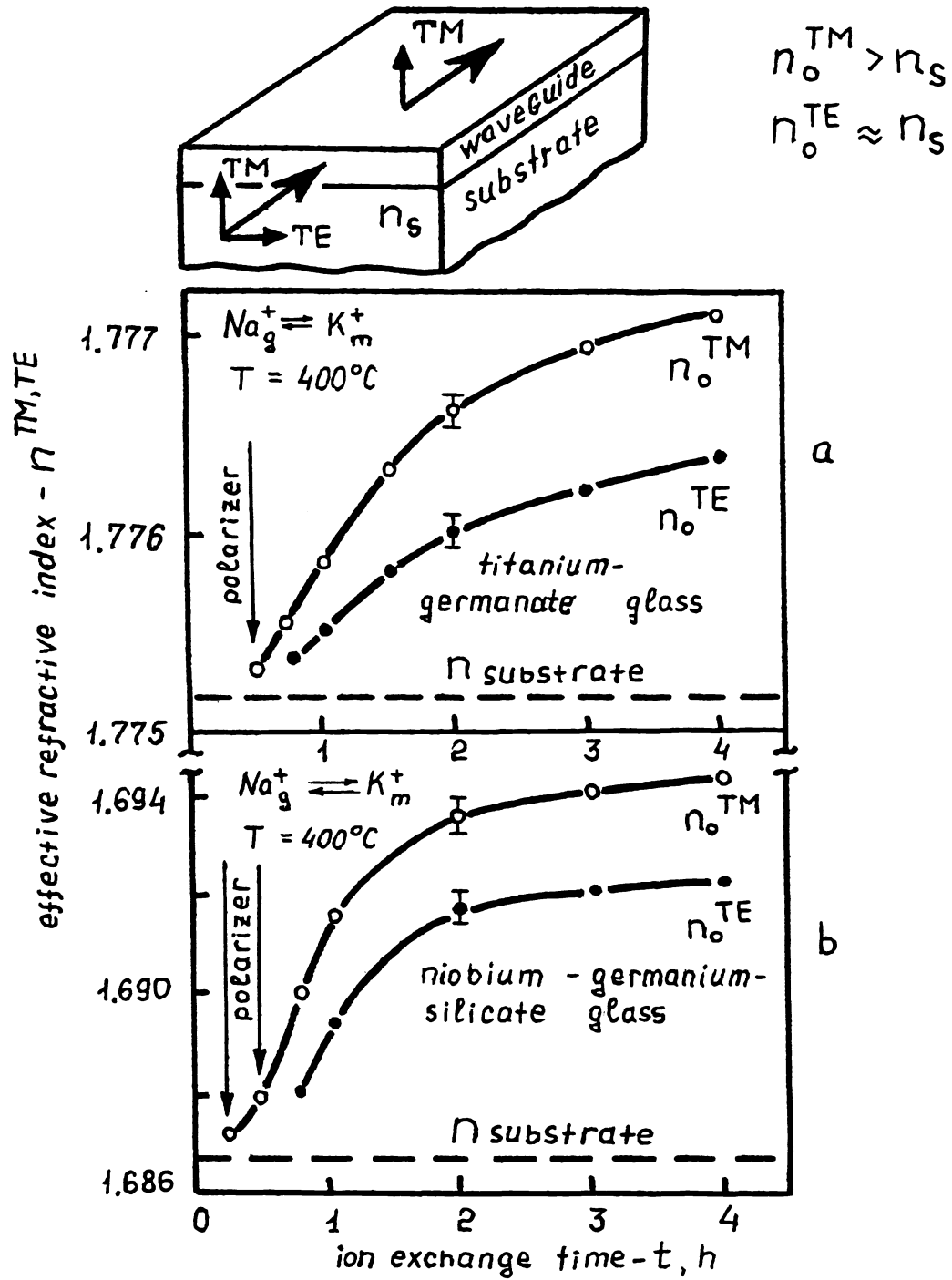


Fig. 5. Glass waveguide polarizer. Effective refractive index of waveguide as a function of ion-exchanged time.

Table 1

Transmitting glasses and waveguide parameters

silicate glasses

glass	main components mol%	n_s substrate $\lambda=0.63\mu\text{m}$	salt $R_g^+ \rightleftharpoons R_m^+$	T °C	t hr	Δn^{TE} $\cdot 10^4$	$n_o^{TM} - n^{TE}$ $\cdot 10^4$	h μm
K-8		I.5140	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	500	4	50	8	18
boro-silicate	B_2O_3 - 10 SiO_2 - 70	I.5150	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	500	2	60	10	18
			CsNO_3 $\text{Na}^+ \rightleftharpoons \text{Cs}^+$	500	2	390	1	3
zirconium-silicate	ZrO_2 - 11 SiO_2 - 72	I.5700	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	500	4	110	20	60
			CsNO_3 $\text{Na}^+ \rightleftharpoons \text{Cs}^+$	500	2	350	1	10
zirconium-germanium-silicate	ZrO_2 - 8 GeO_2 - 10 SiO_2 - 53	I.5610	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	400	0.2	94	20	21
zirconium-niobium silicate	ZrO_2 - 12 Nb_2O_5 - 10 SiO_2 - 61	I.6598	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	450	2	106	15	8
niobium germanium silicate	Nb_2O_5 - 12 GeO_2 - 22 SiO_2 - 46	I.6868	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	490	3	120	35	17
glass-ceramic CO-33M		I.5476	KNO_3 $\text{Li}^+ \rightleftharpoons \text{K}^+$	450	17	30	8	-

Table 1

phosphate glasses

glass	main components mol %	n_s substrate $\lambda = 0.63 \mu\text{m}$	salt $R_g^+ \rightleftharpoons R_m^+$	T $^{\circ}\text{C}$	t hr	Δn^{TE} $\cdot 10^4$	$n_o^{\text{TM}} - n_o^{\text{TE}}$ $\cdot 10^4$	h μm
alumino-silicate-phosphate	Al_2O_3 - 18 SiO_2 - 20 P_2O_5 - 28	I.5002	CsNO_3 $\text{Na}^+ \rightleftharpoons \text{Cs}^+$	450	0.2	170	I	I6
alumino-zirconium-silicate-phosphate	Al_2O_3 - 18 ZrO_2 - 15 SiO_2 - 5 P_2O_5 - 28	I.5053	CsNO_3 $\text{Na}^+ \rightleftharpoons \text{Cs}^+$	450	0.2	350	I	8
alumino-germanium-phosphate	Al_2O_3 - 17 GeO_2 - 24 P_2O_5 - 27	I.5244	CsNO_3 $\text{Na}^+ \rightleftharpoons \text{Cs}^+$	450	0.2	170	I	I7
niobium phosphate	Nb_2O_5 - 30 P_2O_5 - 30	I.7618	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	450	0.2	70	25	I5
magnesium phosphate	MgO - 33 P_2O_5 - 59	I.5141	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	380	9	14	2	-
germanate glasses								
titanium-germanate	TiO_2 - 20 GeO_2 - 60	I.7752	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	400	4	10	10	-
alumino-germanate	Al_2O_3 - 33 GeO_2 - 65	I.6050	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	350	I.	80	II	-

Table 2

Active glasses and waveguide parameters

glass	n_s substrate $\lambda=0.63\mu\text{m}$	salt $R_g^+ \rightleftharpoons R_m^+$	T °C	t hr	Δn^{TE} $\cdot 10^4$	$n_o^{TM} - n_o^{TE}$ $\cdot 10^4$	h μm
laser silicate	I.5700	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	500	4	110	20	60
laser phosphate	I.4935	CsNO_3 $\text{Na}^+ \rightleftharpoons \text{Cs}^+$	450	0.1	495	1	17
photochromic	I.4940	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	400	6	80	14	13
electrochromic	I.7618	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	450	0.2	70	25	15
polychromic	I.4932	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	400	2.5	110	7	26
magneto optic	I.5742	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	500	7	74	20	12
electrooptic	I.8223	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	450	2	56	2	-
glass doped CdS-CdSe	I.5202	KNO_3 $\text{Na}^+ \rightleftharpoons \text{K}^+$	400	1	36	7	14

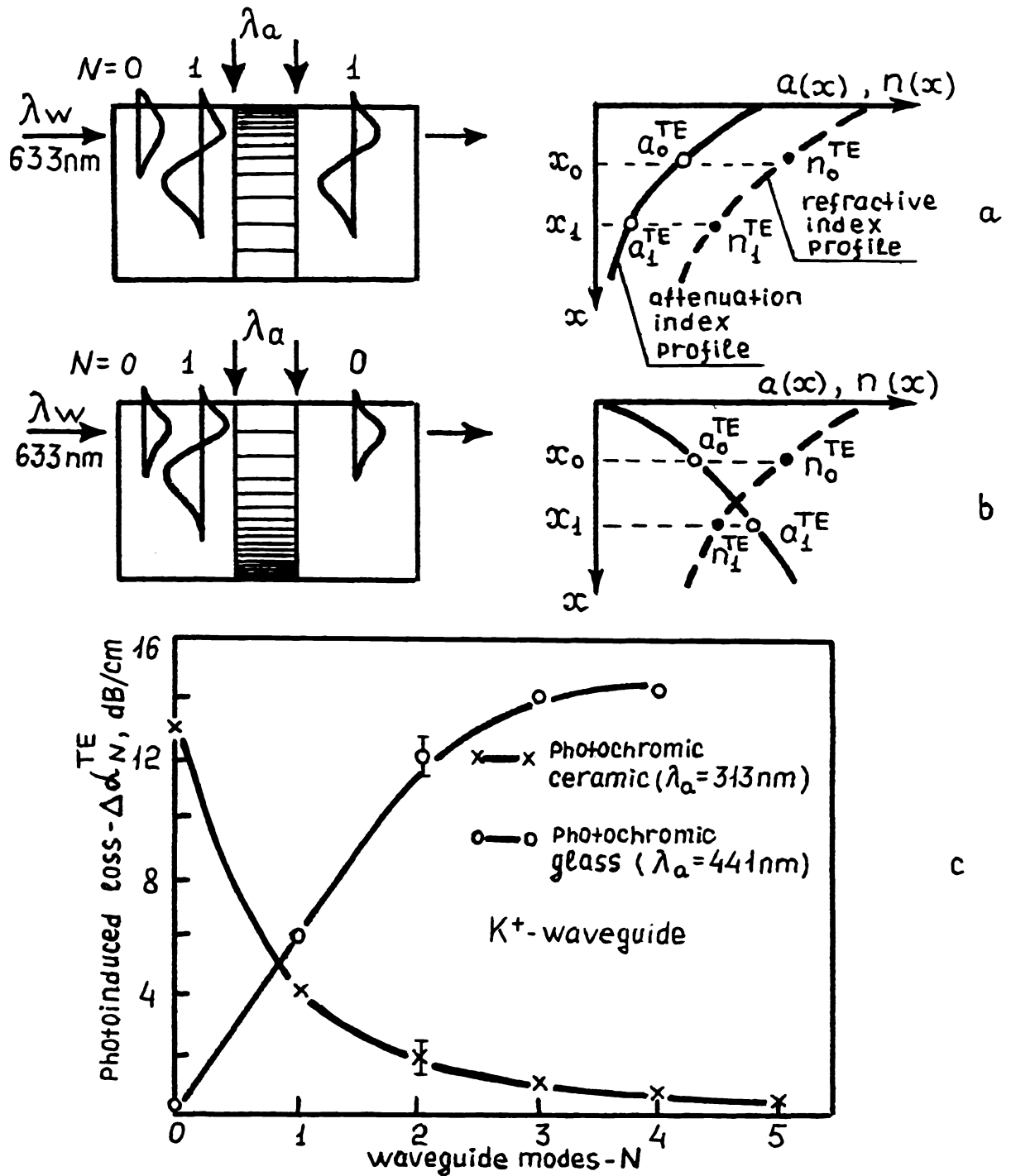


Fig. 6. Examples of spatial selectors of waveguide modes (a,b). These selectors are controlled by external radiation. c - Photoinduced loss as a function of mode number (points was connected for visualizability).

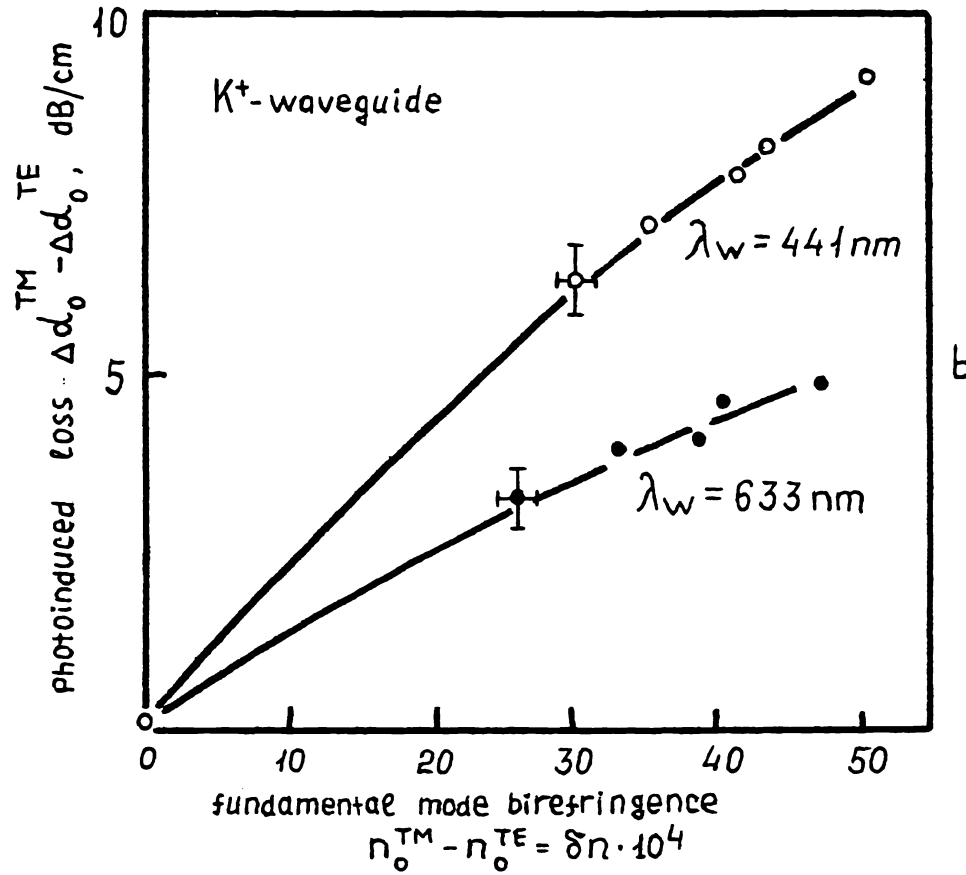
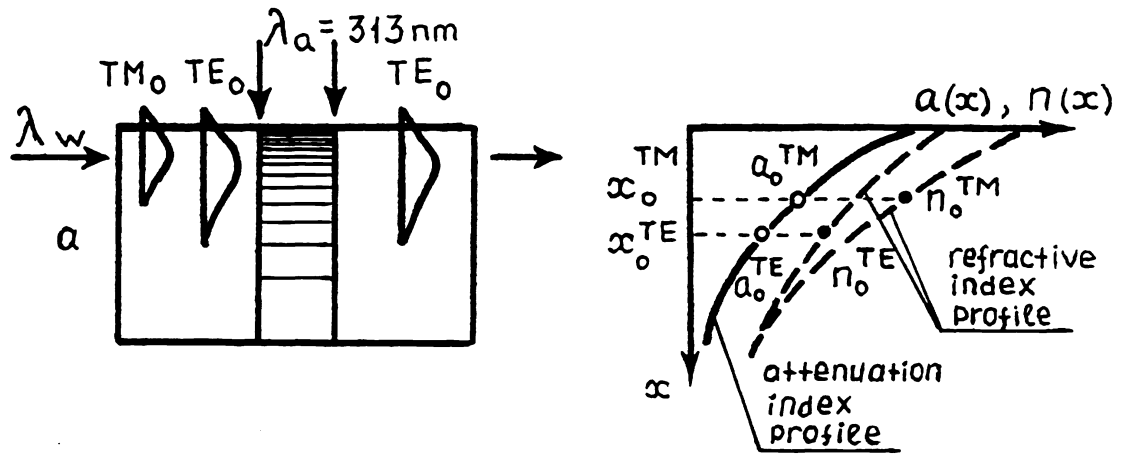


Fig. 7. Example of polarizing selector of waveguide modes (a). The selector are controlled by external radiation. b - Photoinduced loss as a function of fundamental mode birefringence.

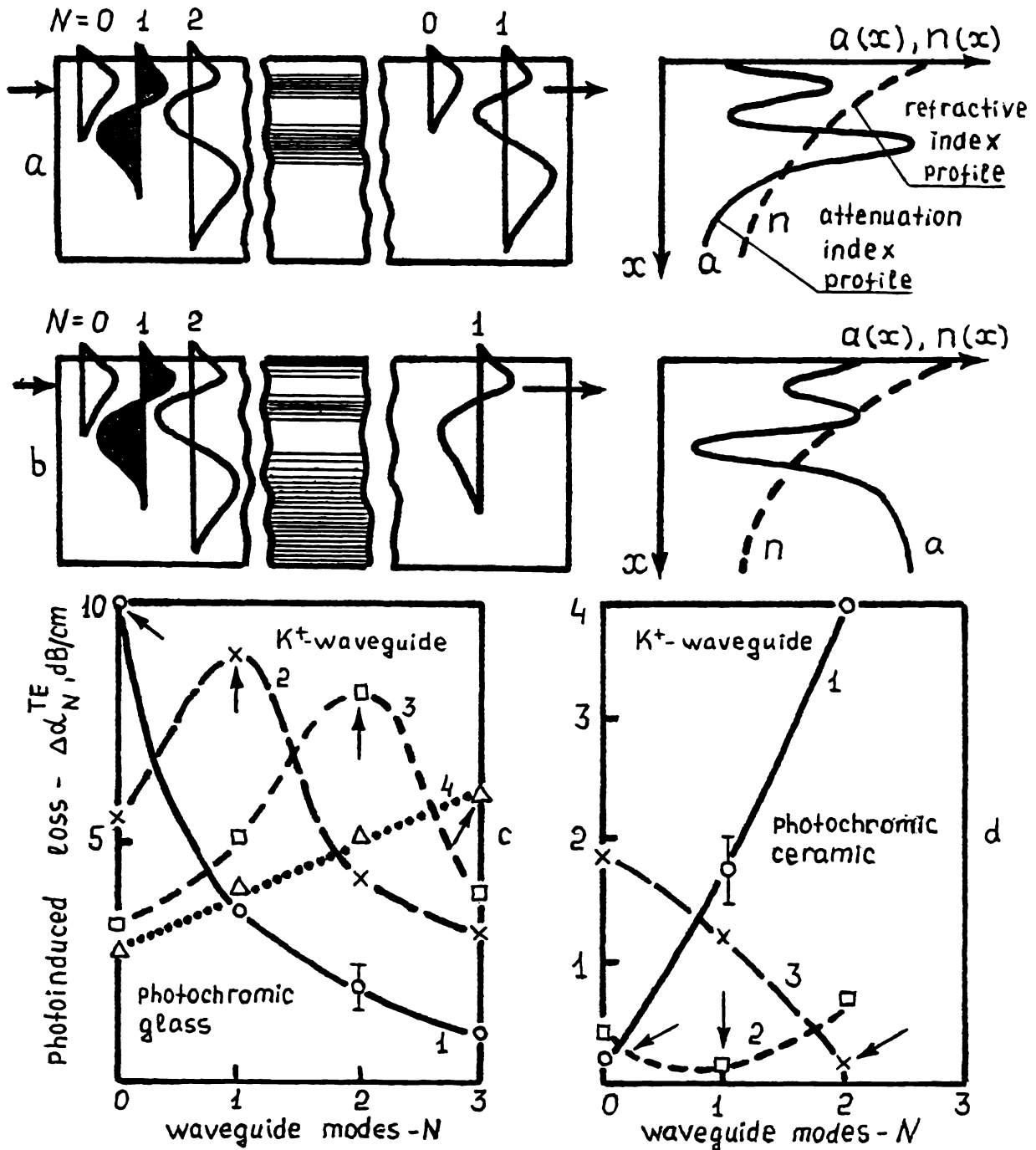


Fig. 8. Examples of spatial selectors of waveguide modes (a,b). These selectors are controlled by waveguide radiation. Waveguide radiation creates negative (a) or positive (b) masks. Photoinduced loss as a function of mode number by radiation excitation of mode $N = 0$ (curve 1), $N = 1$ (curve 2), $N = 2$ (curve 3), $N = 3$ (curve 4) for negative (c) and positive (d) masks.

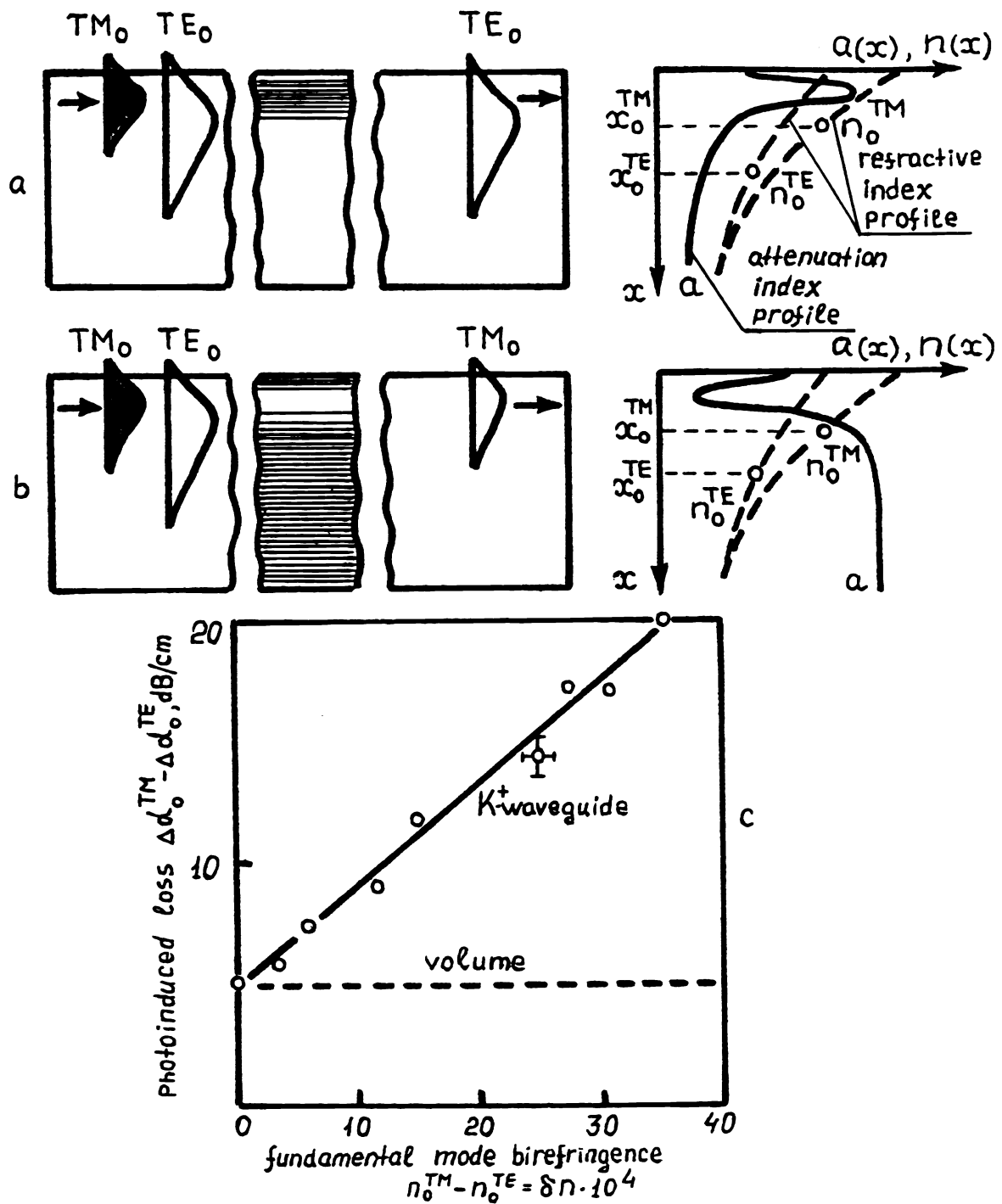


Fig. 9. Examples of polarizing selectors of waveguide mode (a,b). These selectors are controlled by waveguide radiation. Waveguide radiation creates negative (a) or positive (b) masks. c - Photoinduced loss as a function of fundamental mode birefringence.