Critical ray-like propagation modes along graded-index planar optical waveguides

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Graded-index planar optical waveguides and surface compression layers were formed simultaneously in the surface layer of glass plates by ion exchange. A change in the refractometer patterns was observed. Before ion exchange, only a critical ray fringe was observed, but with ion exchange a guided wave fringe appeared on the high effective refractive index side of the 'critical ray' fringe, and the number of guided wave fringes increased. The guided wave fringe or fringes were birefringent, whereas the 'critical ray' fringe was kept non-birefringent. It was concluded that the 'critical ray' propagated along the bottom of a waveguide, ie at the foot of the refractive index distribution.

KEYWORDS: waveguides, optical phenomena, ion-exchange methods

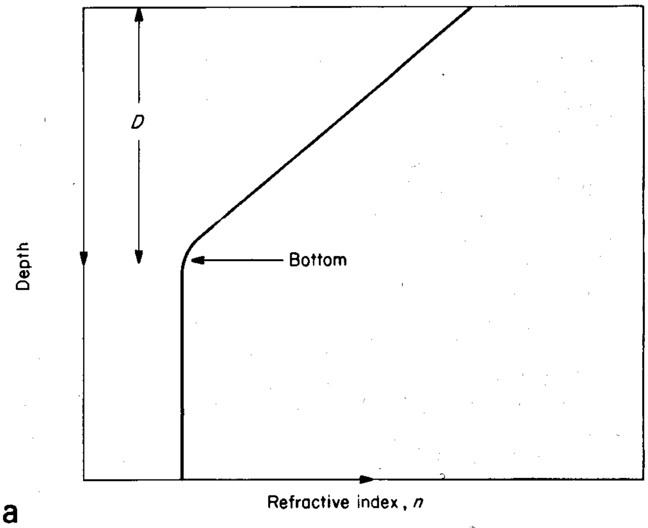
A critical ray can be excited on a glass surface by light incident at the critical angle ϕ_0 for total reflection[1] from an optically denser medium. The ray propagates along the surface for a macroscopic distance. The apparent effective refractive index n_e for the ray is equal to the glass surface index.

When the glass surface is birefringent, due to the photoelastic effect, for example, two linearly polarized critical rays are excited. The difference in the value of n_e between the rays is proportional to the glass surface stress. The principle allows surface stress determination for both flat[2] and curved[3] tempered glasses.

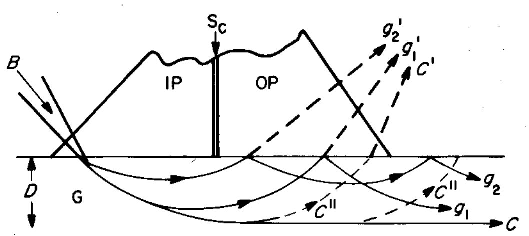
The critical ray plays an important role in accommodating electromagnetic fields at discontinuous boundaries[1]. Its behaviour resembles that of an evanescent wave which is excited by light incident at ϕ_0. This paper reports that a propagation mode, which resembles the critical ray in role and behaviour, exists along graded-index planar optical waveguides.

Although much research has been carried out on guided-wave modes in waveguides[4], the critical ray-like mode had not been forecast either by ray optical or by wave optical analyses. The mode seems to accommodate electromagnetic fields at boundaries where the dn/dx distribution is discontinuous, ie where d^2n/dx^2 gives a sharp peak. Here, n and x represent refractive index and depth, respectively.

In this report, graded-index optical waveguides were formed on glass surfaces by ion exchange (Na^+ in glass) $\leftrightarrow$ (K^+ in KNO_3 melt). Effective index distribution of the propagation mode or modes was observed in relation to the degree of ion exchange. Conventional notations TM and TE are used for light waves which vibrate respectively perpendicular to and parallel with the glass surface.



a



b

Fig. 1 Optical effect in an ion-exchanged glass surface: a refractive index distribution in ion-exchanged surface layer; b — ray optical representation of light propagation in ion-exchanged waveguide layer: n — refractive index; IP — input prism; OP — output prism; Sc — screen; B — laser beam; G — glass; g — guided-wave mode; c — critical ray-like mode; g' — guided-wave mode ray which is refracted out of glass; c' — critical ray-like mode which is refracted out of glass; c'' — fictive path of light energy which is transferred from c to c' by wave optical effect; D — depth of graded-index, waveguide layer (μm)

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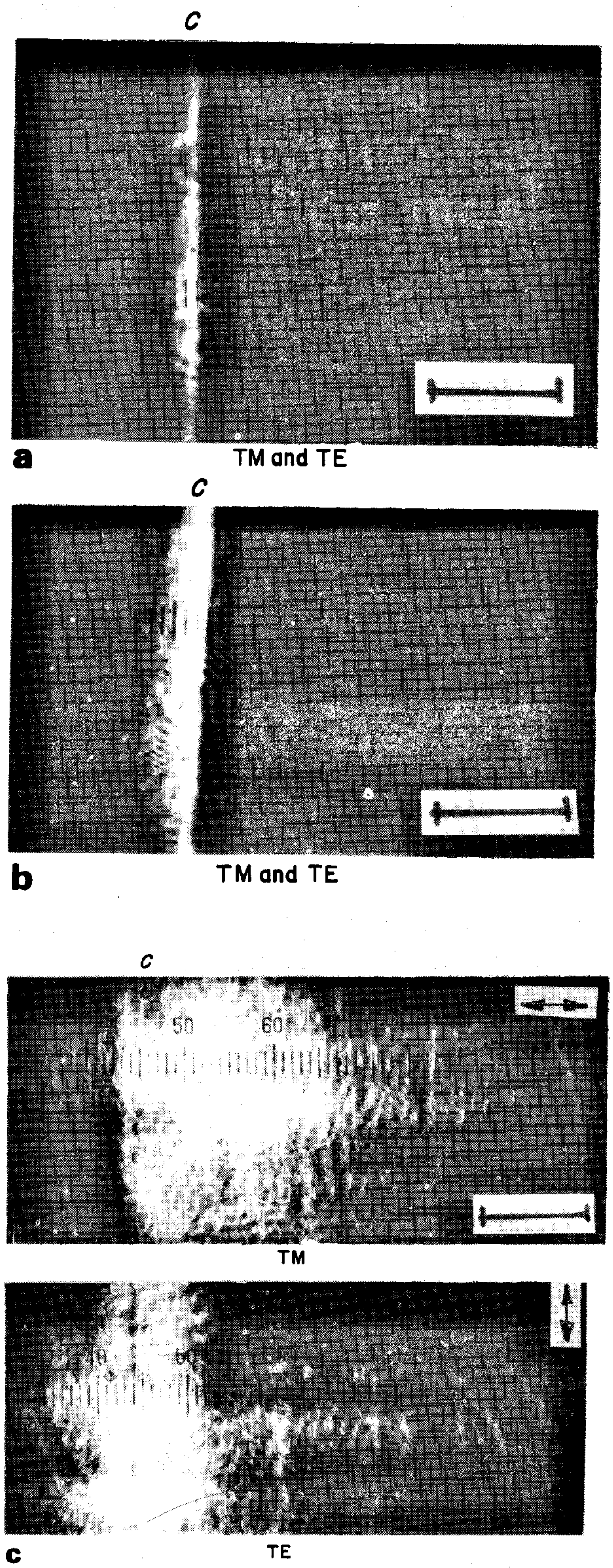


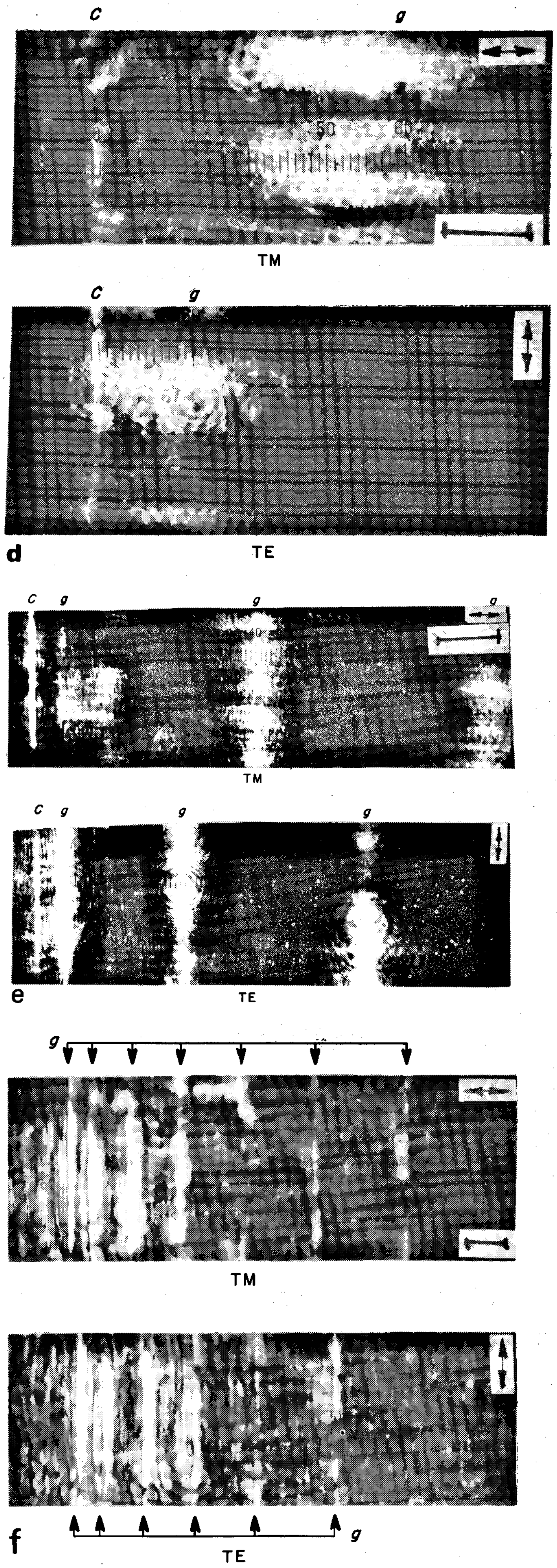
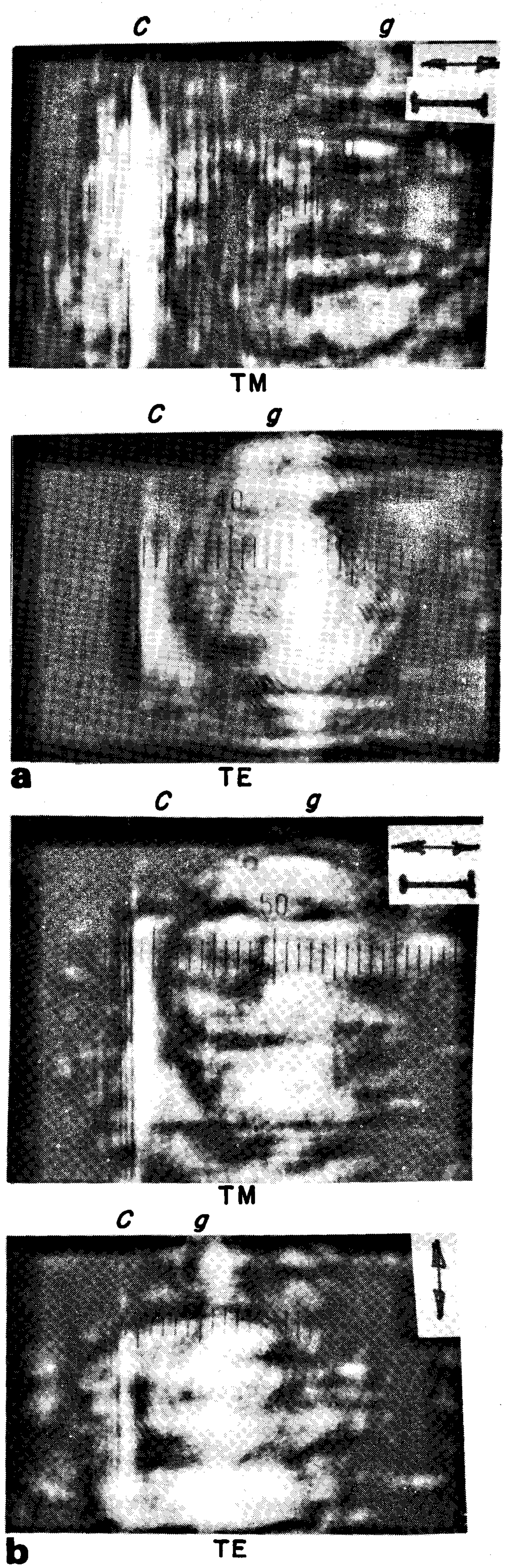


Fig. 2 Ion-exchanged glass surface refractometer patterns: a — Before exchange; b — after 2 minute ion exchange; c — after 8 minute ion exchange; d — after 15 minute ion exchange (D — 3.5 μm; σ_0 — 70 kg mm^{-2}); e — after 60 minute ion exchange (D — 9 μm; σ_0 — 92 kg mm^{-2}); f — after 240 minute ion exchange (D — 17 μm; σ_0 — 78 kg mm^{-2}). C — critical ray; c — critical ray-like mode; g — guided-wave mode; bar — effective refractive index difference Δn for 0.001. Arrows denote vibration direction for linearly polarized light. σ_0 — surface stress (kg mm^{-2}); D — depth of graded-index, waveguide layer (μm)



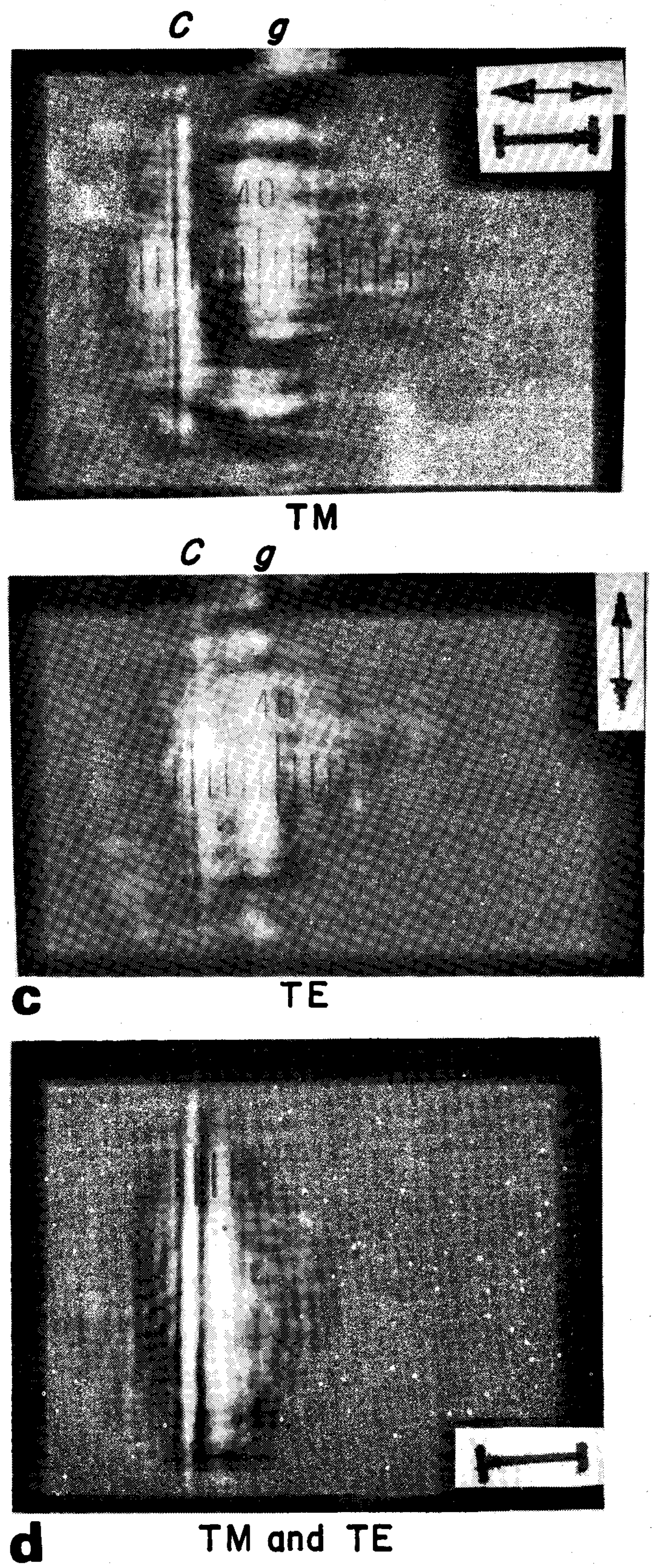
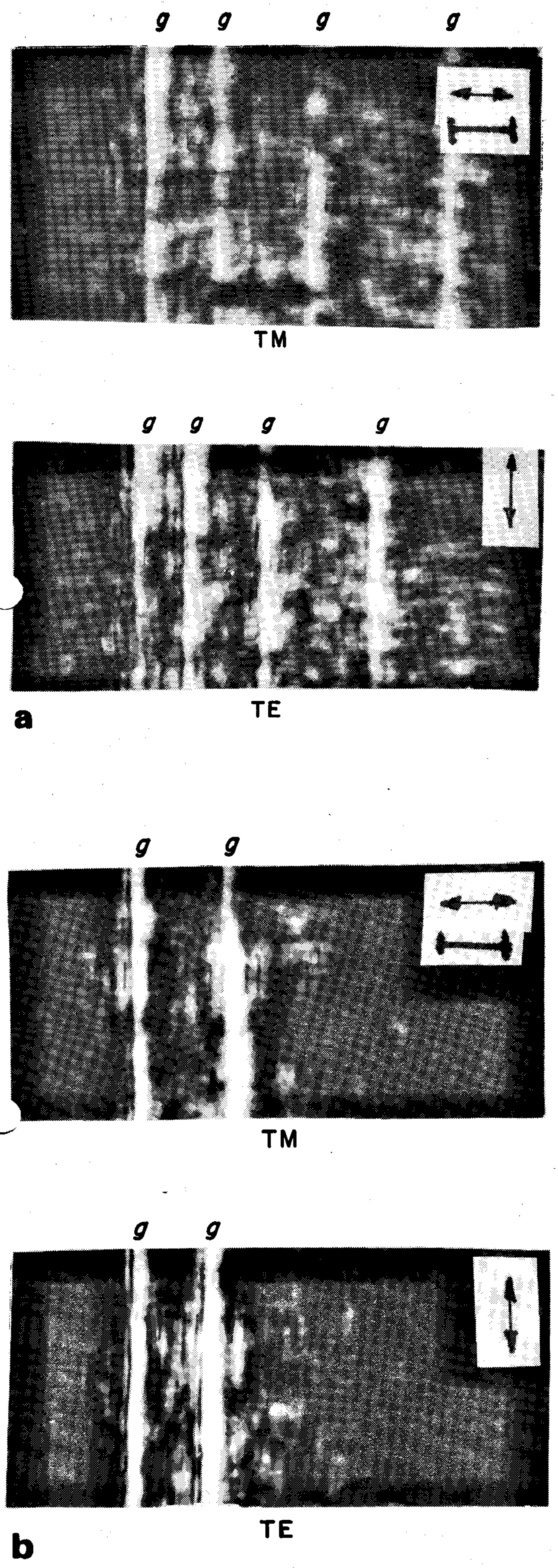


Fig. 3 Change in refractometer patterns by etching a thin waveguide. Etching time increased from a to d. a was ion exchanged for 30 minutes. Notations are as in Fig. 2. D – 3 μm

Experimental procedure

Planar graded-index optical waveguides were formed on the glass surface by alkali ion exchange. The glass was an optical quality soda-alkaline earth, alumina-silica glass for photomask glasses.

The refractive index gradient was built in by (Na^+ in glass) $\leftrightarrow$ (K^+ in KNO_3 melt) exchange in a KNO_3 bath. This exchange simultaneously gave rise to surface compression



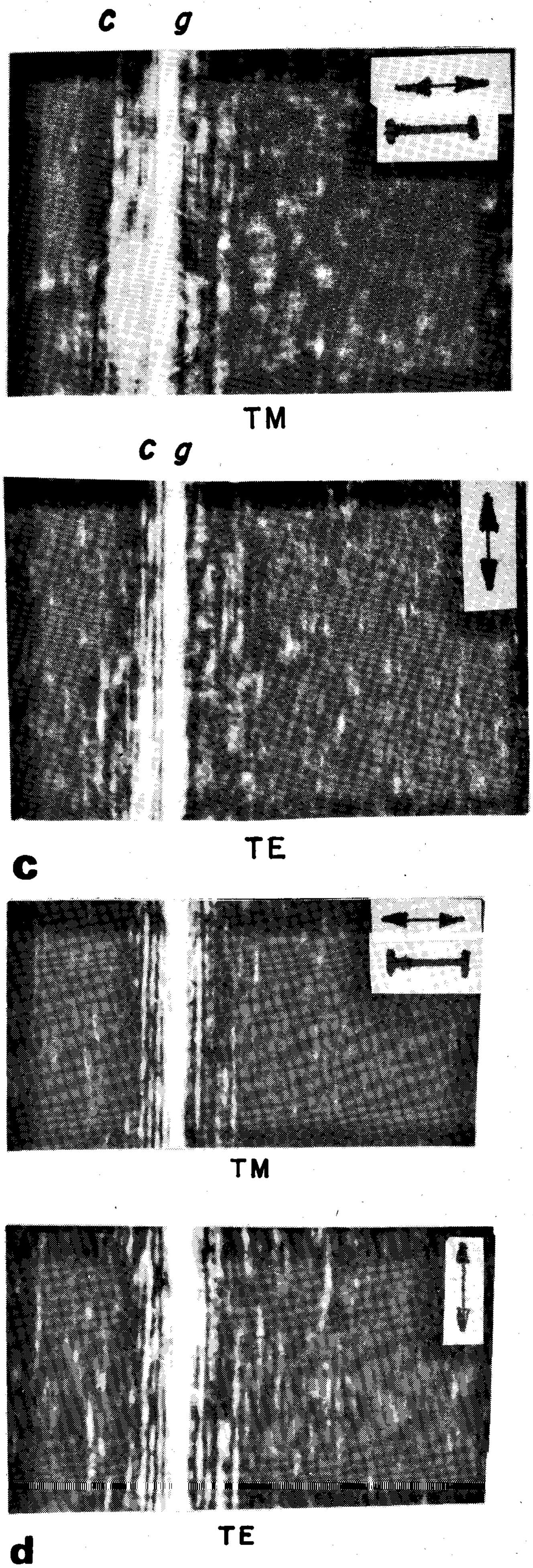


Fig. 4 Change in refractometer patterns by etching a thick waveguide. Etching time increased from a to d; a was ion exchanged for 240 minutes. Notations are as Fig. 2. a — D = 16 μm; σ_0 = 45 kg mm^{-2}. b — D = 9 μm; σ_0 = 10 kg mm^{-2}

stress (chemical tempering). Chemical reagent-grade KNO_3 was contained in a stainless steel vessel. The vessel was heated to 400°C in an electric furnace with temperature control.

Optical arrangement is the same as reported in a previous paper[2,5,6] (Fig.1). The HeNe gas laser beam (1 mW) was injected through a high-index (n = 1.73) input prism to excite propagation modes, if any, in and along the waveguides. The mode waves are extracted by an output prism, and focused by a telescope to form a fringe pattern in the field of view (Figs. 2 – 4). The fringe pattern gave the effective refractive index distribution of the mode wave or waves.

The telescope carried an objective lens (f = 80 cm) and an ocular micrometer (x 10). Immersion liquid (CH_2I_2; n = 1.73) was applied between the prisms and the glass surface.

Surface stress σ_0 and K^+ ion penetration depth (equal to the waveguide thickness) D were estimated from the effective index distribution and number of guided modes in waveguides, by the method reported previously[5]. Surface etching experiments were carried out using dilute hydrofluoric acid.

Experimental results and propagation mode assignment

The results described in the following section may be understood by assuming that a propagation mode exists along the bottoms of waveguides, where birefringence is very low or zero and d^2n/dx^2 is high. The mode will be represented as a critical ray-like mode. The mode appeared to be excited or extracted only when the glass surface-waveguide bottom distance was less than several micrometres.

Critical ray in non-tempered glass

Before ion exchange, the glass surface sustained a critical ray propagation mode (Fig. 2a). The effective refractive index n_e was the same for TM and TE waves, because the surface was stress-free.

Ion-exchange experiment

As ion exchange progressed, the following sequence was observed. First, the luminosity of the critical ray fringe increased (Fig. 2b). This was followed by the appearance of a broad frill at the high-index side of the fringe. This indicated that the ion-exchanged layer became optically thick enough to sustain additional waves. The effective index range of the frill for the TM wave was higher than that for the TE wave (Fig. 2c).

The frills changed into separate broad fringes, while the original fringes were kept sharp (Fig. 2d). Effective indices of the former differed from each other between TM and TE waves, while the latter's TM and TE wave indices were the same. The former were assigned as guided waves in the photoelastically birefringent ion-exchanged layer, and the latter as a critical ray-like propagation mode along the bottom of the ion-exchanged layer where stress was approximately zero.

The number of birefringent guided wave mode fringes increased as non-birefringent critical ray-like mode fringes vanished. The birefringent guided-wave fringes gradually became sharp (Figs. 2e and 2f). Qualitative observation shows that, as long as a critical ray-like mode fringe was observed, the mode could propagate for a distance of several millimetres.

Surface etching experiments

Surface etching of a thin waveguide resulted in a decrease in the number of guided-wave modes, while the critical ray-like mode was invariant in appearance and behaviour. Only one broad guided-wave mode fringe was left for TM waves, while the critical ray-like mode fringe was kept unchanged for TE waves (Fig. 3a).

Effective index differences between the guided-wave mode and the critical ray-like mode decreased (Fig. 3b), and simultaneously a frill was formed at the low-index side of the guided-wave mode fringe to connect the guided-wave and critical ray-like fringes. The fringes fused together to form a broad fringe (Figs. 3c and 3d), and finally the fringe became sharper (Fig. 3d). The effective index was the same for TM and TE waves.

Etching of a thick waveguide gave a decrease in the number of guided-wave mode fringes (Figs. 4a and 4b). With the decrease of waveguide thickness D a critical ray-like mode fringe appeared (Figs. 4b and 4c). A sequence similar to that observed for the thin waveguide followed (Figs. 4c and 4d), except that, in the thick waveguide case, the critical ray-like mode fringe was less distinct.

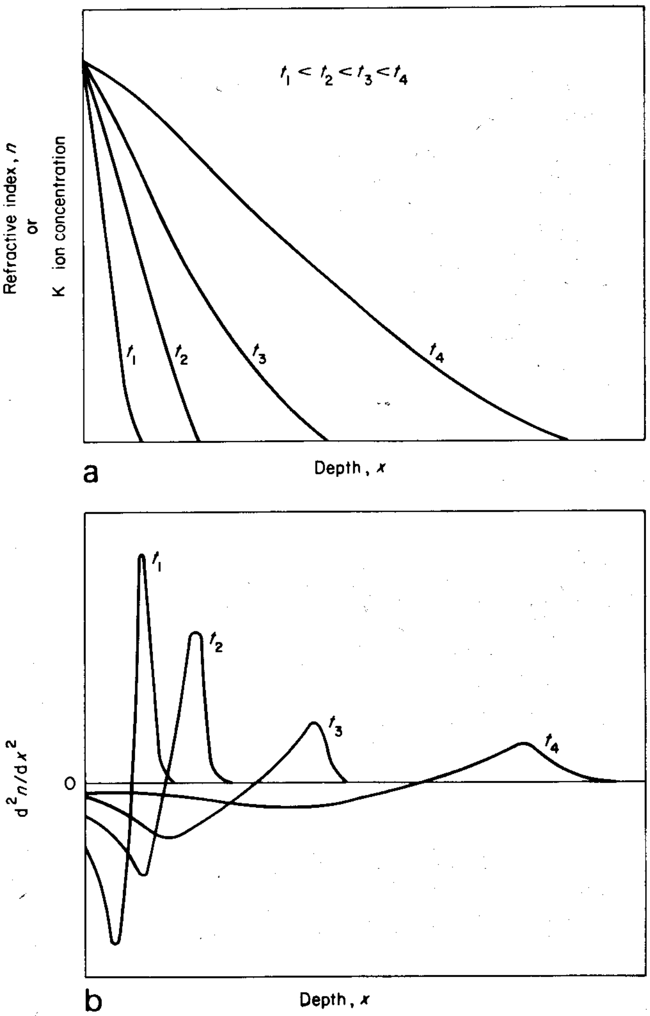


Fig. 5 Sketch of distributions in: a – refractive index n; and b – d^2n/dx^2 along depth x. t is the ion exchange time

Discussion

The propagation mode, which we have called a critical ray-like mode in the previous section, can be assumed to be a modification of a critical ray in that a critical ray submerges into glass to form a critical ray-like mode as the graded-index layer grows. Unlike to guided-wave modes, the effective indices of critical ray-like modes for TM and TE waves are the same, indicating that the mode propagates along the bottom of the graded-index layer where the stress and photoelastic effect are approximately zero and d^2n/dx^2 is large. The mode is more distinct for the thinner waveguide which gave a larger d^2n/dx^2 at the bottom (Fig. 5).

Thus, the critical ray-like mode seems to accommodate electromagnetic fields at an anomaly of the refractive index distribution. Modes of guided waves are well known and well analysed. They depend on refractive index distribution and on photoelastic birefringence in a graded-index layer. They are therefore useful for non-destructive surface stress determination[5].

The reasons that critical ray-like modes have not been observed or discussed before might be due, from an experimental point of view, to the fact that, unlike guided-wave modes, critical ray-like modes are localized to the bottom of a waveguide and can be excited along and extracted from the bottom only when the distance from the surface to the bottom of the guide is less than several micrometres.

The excitation condition is also important. A critical ray-like mode can be excited practically only by injection of light at the critical angle. Less energy is injected into a critical ray-like mode than into guided-wave modes, and a critical ray-like mode is distinct only when d^2n/dx^2 at the bottom of the waveguide is large.

In addition, from the theoretical point of view, the mode is not compatible with ray optics. Most detailed analyses were based on smooth refractive index distributions, and on predetermined smooth functional representation of electromagnetic waves. As long as the existence of the mode was not assumed, the mode could not be inferred from such analyses. Thus, although the critical ray-like mode is important theoretically, it is not so in practical integrated optics.

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