Planar waveguides in multicomponent glasses fabricated by field-driven differential drift of cations

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The fabrication of planar waveguides by a constant-current thermal poling procedure in multicomponent glasses rich in alkali or alkaline earth ions is described. Near the anode, the DC electric field applied to the substrate separates the mobile cations into regions according to their mobility. Each region presents a different refractive index, allowing a waveguide to be formed. This method produces waveguides with an index increase greater than 10^{-2} in soda-lime glass with no external ion source, and the waveguides are buried beneath the substrate surface without an additional step.

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Multicomponent glasses are promising materials for a wide range of advanced integrated optical devices. In particular, efficient Yb/Er energy transfer and high gain for optical amplification, high photosensitivity for grating writing, and high $\chi^{(3)}$ for all-optical switching,[1] have been demonstrated in multicomponent silicate glasses, the latter promising the realization of high $\chi^{(2)}$ electro-optic waveguides through thermal poling. In principle, all these phenomena may be combined in one material in which waveguides can be fabricated to realize a low-cost multifunctional integrated optical technology. Before efficiently poled waveguides may be realized in multicomponent glasses, information is needed on the ionic redistribution and refractive index changes occurring when the glass substrate alone is poled. Further, the design of electrodes for poling channel waveguides will require knowledge of the response of the substrate material surrounding the waveguide to the poling process. Margulis et al. showed that channel waveguides could be realized by applying a thermal poling process to a soda-lime glass substrate using a deposited aluminium film anode in which narrow channels were opened by photolithography[2]. Waveguide formation resulted from reduction in the refractive index due to sodium ion depletion under the electrode either side of the channel opening, and under the channel due to fringing fields and the evolving current path.

In this Letter, a study of the effects of constant current thermal poling of soda-lime glass substrates using uniform circular deposited electrodes is reported. In this case it was found that waveguides were formed directly under the anode. Cross sectional compositional profiling by X-ray Energy Dispersion Analysis (EDX) showed that, while the surface is depleted of sodium ions, a buried region of elevated calcium and magnesium ion content (referred to as the accumulation region) forms beneath the surface within the Na^+ depletion region. Waveguide mode profiling by near-field imaging confirmed that the waveguide mode is buried and that it is localized within this accumulation region. The modal effective indices

of the slab waveguides fabricated in soda lime glass were measured at a wavelength of 633nm and related to the duration of the process. Waveguides have also been fabricated in BK7, SFL6 and Crown glasses using this technique, demonstrating its wide applicability to glasses rich in alkalis or alkaline earths.

Three soda-lime glass substrates (Fisher Premium), 25 mm square by 1 mm thick, were cleaned, and circular 7 mm diameter aluminium electrodes of thickness 400nm were deposited centrally on both faces by vacuum evaporation through a shadow mask. To apply an electric field at elevated temperature, each sample was placed in a holder with the cathode pressed onto a silicon wafer and a high-voltage (HV) supply was connected between the anode and the silicon wafer. The assembly was placed in a vacuum chamber with a radiant heater, the chamber was pumped to below $3x10^{-6}$ mbar, and the sample was heated until it reached equilibrium at 200°C. The HV supply was then turned on and a variable voltage was applied to maintain a constant external current of 20 μA for the process time. Each sample was cooled down to room temperature with a constant voltage applied equal to that achieved at the end of the poling process. The external current fell to zero approximately 2 minutes after commencement of cooling. The temperature, current and the applied voltage were continuously recorded from the application of the initial voltage until the samples reached room temperature.

The soda lime samples were processed for 60, 90 and 120 minutes. The voltage applied to maintain a constant current of 20 μA rose approximately linearly over the entire duration, in agreement with results reported by Garcia et al[3]. In all cases the initial value was approximately 90V and the final values attained were 1.36 kV, 2.05 kV and 2.51 kV after 60,

90 and 120 minutes respectively. This shows that the voltage drop through the negatively charged layer depleted of sodium ions[3] increases linearly with the charge transported.

Following the poling process, the electrodes were removed from all samples using a commercial aluminum etchant and the anode surface region was observed under white light illumination. In each case, the poled region appeared uniformly colored, exhibiting a red to pink hue, indicating the formation of a layer with a uniform refractive index different from that of the bulk. Waveguide modes were detected in the region below the removed anode using the standard prism coupling technique, indicating a region of increased refractive index near the surface. Figure 1 shows the effective indices, N_{eff}, measured at a wavelength of 633nm in the center of the poled region, with an error of $\pm$ 2 x 10^{-4}, for the TE and TM polarizations. The waveguide modes show increasing effective indices with poling time, and the TE-polarized modes showed slightly higher effective indices than TM-polarized modes, as would be expected in a stressless isotropic material. If the substrate index is taken to be 1.512 at this wavelength, then the increase in index due to this process is greater than 10^{-2}.

To study how the waveguides had been formed, the samples were diced and end-polished to allow EDX line scans of the cross-sectional concentration profiles and near-field measurements of the waveguides modal profiles. The depth distributions of sodium, calcium and magnesium ions under the anode, obtained by EDX for the sample poled in vacuum for 120 minutes, are shown in Figure 2a where the surface is at 0μm. It can be seen that the sodium ions are strongly depleted at the surface, as expected, and that the Ca^{2+} and Mg^{2+} ions have become depleted at the surface but concentrated close to the edge of the sodium depletion region. The calcium ion accumulation agrees with Lepienski's compositional measurements on poled soda-lime glass[4]. Ca^{2+} and Mg^{2+} ions are so much less mobile than

Na^+ ions that they do not participate in normal ion-exchange and field-assisted ion-exchange processes in soda-lime glass. We believe that the drift of the much less mobile Ca^{2+} and Mg^{2+} ions, in this case, is due to the high electric field built up in the sodium depletion region during poling. The drift of Ca^{2+} and Mg^{2+} ions is restricted to the depletion region since the electric field that drives the Na^+ ions in the highly conductive bulk glass is too low to drive the Ca^{2+} and Mg^{2+} ions. The accumulation of Ca^{2+} and Mg^{2+} is caused by this differential drift that forces the Ca^{2+} and Mg^{2+} ions to occupy vacancies left by depleted Na^+ ions, but does not allow them to penetrate further into the bulk.

Light from a He-Ne laser at a wavelength of 633nm was coupled into the waveguides using a monomode optical fibre and their modal intensity profiles were measured by imaging onto a CCD camera using a 63× objective. The position of the substrate surface was determined by imaging the illuminated endface of the waveguide with the same set up. These measurements were calibrated using a micrometric graticule replacing the waveguide edge. An unpolarised mode profile obtained by the imaging setup is superimposed on Figure 2, with the scales and the absolute positions of the depth axis aligned with an accuracy of ±0.25μm, showing that the waveguide mode is buried substantially beneath the substrate surface and that it is localized in the accumulation region of high Mg^{2+} and Ca^{2+} concentration. This supports the view that the packing of the two alkaline earth components of the glass creates a waveguiding layer with a higher refractive index than that of the depletion region and the bulk glass.

Buried waveguides were also found in BK7 glass processed at 300°C and under the same electrode and current conditions. The ionic concentration and mode profiles of a sample processed for 90 minutes are shown in Figure 2b. A pronounced accumulation peak of K^+ ions in the sodium depletion region forms a waveguide buried under a layer depleted of

sodium and potassium, and waveguiding was confirmed by prism-coupling. The confinement of the waveguide mode to the potassium-rich region beneath the glass surface confirms that the waveguide is formed in the accumulation region rather than by simple compaction of the glass. From these results we expect that waveguides may be formed in this way in many silicate glasses containing more than one alkali or alkaline earth ion with significantly different mobilities. Preliminary measurements have shown that poling of SFL6 and crown-type glasses for 90 minutes also yields waveguide modes and we believe that these waveguides were also formed by differential drift between Na^+ and other less mobile ions in these glasses.

In this Letter we have shown that planar waveguides may be created by applying a "poling" procedure with uniform electrodes to a homogeneous glass substrate containing more than one species of alkali or alkaline earth ion. The index increase produced by this method is greater than 10^{-2} for soda-lime glass, and the waveguides are buried beneath the substrate surface without any additional step. The buried waveguides are formed at the lower edges of the Na^+ depletion regions by the accumulation of the less mobile ions, K^+ in BK7, and Ca^{2+} and Mg^{2+} in soda-lime glass. This technique is expected to be applicable to a wide range of multicomponent glasses and may contribute to the realization of poled glass waveguides for nonlinear applications.

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Notes

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Figure Captions

Figure 1 Modal effective indices against poling time.

Figure 2 Concentration distributions of mobile ions under the anode after poling with 20μA a) for 120 minutes in soda-lime glass at 200°C and b) for 90 minutes in BK7 at 300°C. The mode intensity profile of the resulting waveguide is also shown.

Figure 1 Brennand Optics Letters

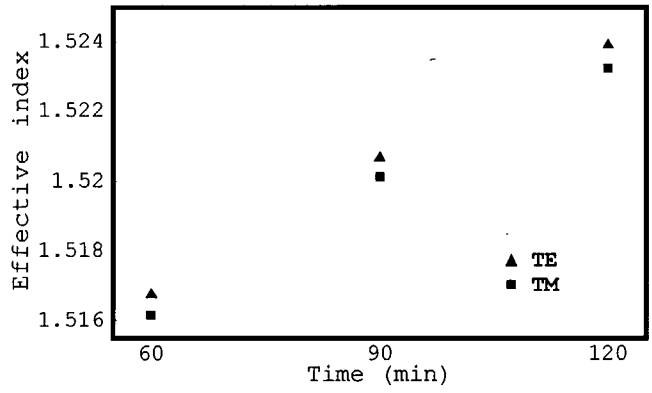

Figure 1 Modal effective indices against poling time.

Figure 2 Brennand Optics Letters

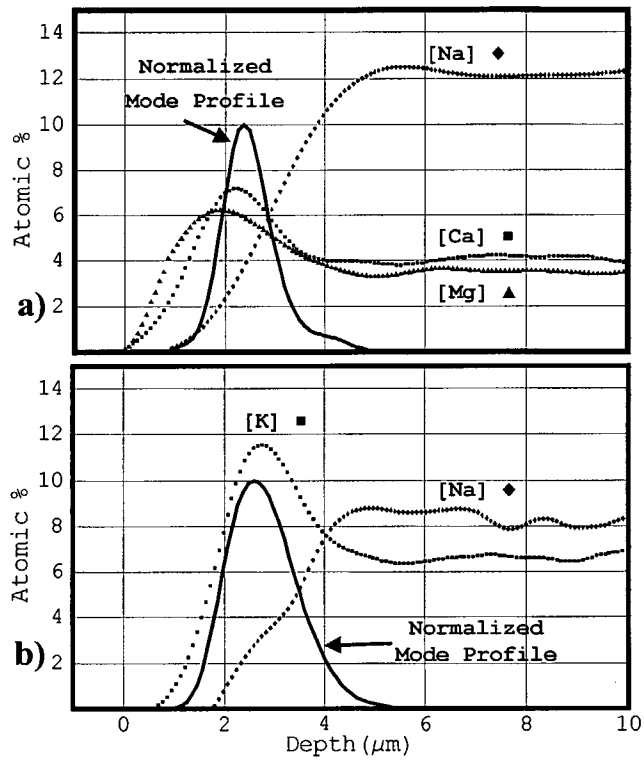

Figure 2 Concentration distributions of mobile ions under the anode after poling with 20μA. a) for 120 minutes in soda-lime glass at 200°C and b) for 90 minutes in BK7 at 300°C. The mode intensity profile of the resulting waveguide is also shown.