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Novel fabrication process of planar waveguides in rare-earth doped fluoroindate glasses

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We report the successful fabrication of planar waveguides in rare-earth doped fluoroindate glass substrates. A new procedure for waveguide fabrication using a thermally evaporated AgF nonmetallic film was developed. The refractive index changes of more than 0.03, associated to low propagation losses achieved, open new perspectives and show the potentiality of using this glass family toward further developments in fabrication and design of integrated optical devices for optical communication wavelengths. © *1995 American Institute of Physics.*

Fluoroindate glasses are now emerging as a promising group of halide glasses for optical amplifiers and fiber lasers.[1–8] In the midinfrared range (up to 8 μm), these glasses present higher transparency compared to the fluorozirconate glasses, they are more stable against atmospheric moisture and their band gap is in the UV region, around 200 nm. The fluoroindate glasses have been successfully doped with rare-earth ions and the spectroscopical studies[4–7] indicate small nonradiative relaxation rates of the dopant ions levels which is due to their smaller phonon energies in comparison with other glasses. Also, frequency upconversion processes have been demonstrated to be very efficient in this material.[8] Clearly, because of their spectroscopic properties, the rare-earth doped fluoroindate glasses exhibit adequate characteristics to be used for compact devices based on optical waveguides. However, the feasibility of such guiding structures in this material has not been demonstrated up to the present. In this letter, we report a demonstration of the successful fabrication of optical waveguides in rare-earth doped fluoroindate glasses.

The substrates used in the present work have the following compositions: (mole %) 37 InF_3–$20ZnF_2$–$16BaF_2$–$20SrF_2$–$2GdF_3$–2NaF–$1GaF_3$–$2TmF_3$ (sample A and C); and (mole %) 38.95 InF_3–$30ZnF_2$–$16BaF_2$–$20SrF_2$–$2GdF_3$ –2NaF–$1GaF_3$–$0.05PrF_3$ (sample B). The substrate preparation was done using the procedure of Refs. 5–8. InF_3 was obtained by fluoration of In_2O_3 at 400 °C with NH_4F and HF in a platinum crucible. Then, all the fluoride components were mixed and heated in a dry box under argon atmosphere at 700 °C for melting and 800 °C for finning. After this process the melt was poured and cooled into a preheated brass mold. The obtained glass substrates have good optical quality and are nonhygroscopic. Their refractive index, $n_1 = 1.503 \pm 0.005$, at 632.8 nm was determined with a refractometer.

Initial processing of the substrates for waveguide preparation involved cutting and polishing the glass to optical quality. The samples were mechanically polished with diamond paste and washed with DI water and a special detergent because common organic solvents such as alcohol and acetone damage the substrate surfaces. Single and multimode planar waveguides were made by modifying the refractive index near the surface of the glass through diffusion of an AgF nonmetallic film. An AgF film (thickness: ⩾70 Å) was produced by resistive thermal evaporation onto the samples and the film diffusion was achieved at 300 °C during different time intervals ranging from 1 to 8 h. It is important to note that conventional methods were unsuccessful to obtain waveguides in the fluoroindate glasses.[9]

The number of waveguide modes and their effective refractive indices were measured using the prism-coupling method.[10] Figure 1 shows the refractive index profile for three waveguides where the points represent the experimental values of the mode's effective refractive indices. The refractive index profiles were inferred using the method described in Ref. 11 which is based on the inversion of the WKB formula. This method does not require any initial assumption for the profile function and uses only the experimental values of the effective refractive indices. The corre-

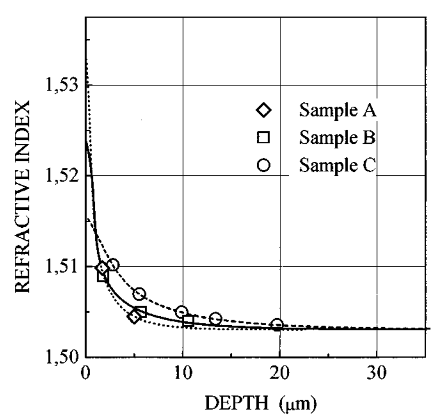

FIG. 1. Refractive index profile of the fluoroindate glass planar waveguides. The solid lines were obtained using the method introduced in Ref. 11.

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TABLE I. Dependence of the waveguide parameters on t (the duration of the AgF film diffusion process). Δn is the maximal refractive index change calculated as the difference between the refractive index of the surface and substrate.

Sample	t (h)	Number of modes	Δn
A	2	2	0.0302
B	4	3	0.0209
C	8	5	0.0125

sponding results are represented by the solid lines in Fig. 1.

The dependence of the waveguide parameters on the duration of the diffusion process is illustrated in Table I where we indicate the number of modes obtained for each waveguide as well as the maximal refractive index change Δn.

To determine the diffusion coefficient D, we approximate the waveguide index profile by the function $n(x) = n_1 + \Delta n \,\mathrm{erfc}(x/\delta)$, $x \geqslant 0$, where erfc is the complimentary error function, $\delta = \sqrt{4Dt}$ is the effective penetration depth, and $x=0$ represents the air-glass interface such that $n(x)=1$ when $x<0$. The values obtained for the diffusion coefficient were $D=1\ \mu m^2/h$ for samples A and B, and $D=2\ \mu m^2/h$ for sample C. The larger value obtained for the last sample is probably due to the long diffusion time used.

The propagation losses of the waveguides prepared were determined by a photometric method which measures the scattered light from the side of the waveguide using a camera coupled with a computer. The scattered light intensity is very weak and the losses measured were dependent on the AgF diffusion time and the film thickness. For the single mode waveguides prepared with a 70 Å AgF film thickness and diffusion time of 1.25 h, the measured propagation losses were smaller than 2.4 dB/cm at 632.8 nm.

In summary, we have developed a method to fabricate planar waveguides in rare-earth doped fluoroindate glasses. This method of preparing waveguides in this kind of glass opens new prospects in fluoroindate glass research and development. We anticipate the potential of these waveguides for devices operating in the communications wavelengths to be very promising since the rare-earth doped fluoroindate glass exhibits small nonradiative relaxation rates for the rare-earth ions. Extension of this research to develop channel waveguides structures and its characterization is in progress.

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