Planar waveguides formed in a new chemically stable Er^{3+}/Yb^{3+} co-doped phosphate glass

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A new Er^{3+}/Yb^{3+} co-doped phosphate glass has been prepared, which exhibits good chemical durability and spectral properties. Planar graded index waveguides have been fabricated in the glass by Ag^+-Na^+ ion exchange in a mixed melt of silver nitrate and potassium nitrate. Ion exchange is carried out by varying the process parameters such as temperature, diffusion time, and molten salt compositions. The diffusion parameters, diffusion coefficients, and activation energy are determined by the guidelines of fabricated waveguides, which are determined by the input prism coupling technique.

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Recently, Er^{3+}-doped waveguide amplifiers (EDWAs) have received a great attention because of their reducing cost and size of the optical amplifiers[1]. Different technologies, such as ion-exchange[2], glass-on-silicon[3], sol-gel[4], femtosecond laser writing[5], and thin film sputtering[6], have been employed to fabricate integrated optical devices on glass substrates. Among these, ion-exchange is the most common way utilized because of its simplicity and low cost. Recently, we designed and developed a new chemically stable Er^{3+}/Yb^{3+} co-doped phosphate glass WM1, which exhibits good chemical durability in boiling distilled water and excellent spectroscopic properties[7]. The chemical durability is characterized by the weight-loss of the glass and found to be 1.45×10^{-5} $g\cdot cm^{-2}$ in boiling water, which is comparable to that of Q-246 silicate glass and Kigre's commercial glass. The fluorescence lifetime of Er^{3+} ions is 7.9 ms and the stimulated emission cross section at 1.533 μm is 0.72×10^{-20} cm^2, which is higher than that reported for IOG-1 phosphate glass[8]. The exchange process is in fact largely influenced by the glass substrate, therefore major adjustments are required for new substrates, and preliminary studies of diffusion properties of glass hosts are required for subsequent fabrication of active waveguides. In order to precisely understand the diffusion properties of WM1 glass in ion exchange process, we carry out Ag^+-Na^+ ion exchange by varying process parameters such as molten salt concentration, diffusion time, and ion exchange temperature.

WM1 glass was prepared from high purity chemical materials. It was first melted in a high quality quartz crucible and then proceeded the refining and stirring in a platinum crucible at an appropriate temperature to get homogeneous glass. Glass without bubble and striate was chosen as the ion exchange sample. Six surfaces of the glass sample with a dimension of $30\times15\times2$ mm^3 were polished to high optical quality. Mixed molten salt KNO_3+AgNO_3 was utilized for ion exchange experiments. Planar waveguides were formed by immersing precleaned and preheated glass samples into the mixed molten salt. Three different molten salt compositions were used in ion exchange process. Salt bath temperature was controlled at $335-355$ °C, and ion-exchange time changed from 120 to 240 minutes. The input prism coupling method in conjunction with a He-Ne laser was used to determine the effective refractive indices of the planar waveguides. The mode effective indices of waveguide were determined by the formula

$$n_{\mathrm{eff}} = \sin\theta\cos\delta + (n_{\mathrm{p}}^2 - \sin^2\theta)^{1/2}\sin\delta, \tag{1}$$

where δ is prism angle, n_{p} is the refractive index of prism, and θ is the synchronous angle of mth order mode.

The diffusion equation for the diffusing ions can be derived from Fick laws. These laws describe, in the context of irreversible thermodynamic processes, the flux of two chemical species i of concentration C_i through an interface. Without any external electric field Fick laws lead to an equation of diffusion

$$\frac{\partial C}{\partial t} = \frac{D_{\mathrm{Ag}}}{1-\alpha C}\nabla^2 C + \frac{\alpha D_{\mathrm{Ag}}}{(1-\alpha C)^2}(\nabla C)^2, \tag{2}$$

where D_{Ag} and D_{Na} are the diffusion coefficients of Ag^+ and Na^+, respectively, $\alpha = 1-(D_{\mathrm{Ag}}/D_{\mathrm{Na}})$ is the Steward coefficient, and C is the silver concentration.

In the particular case when $D_{\mathrm{Ag}} = D_{\mathrm{Na}}$ and for a one-dimensional problem, Eq. (2) has a simplified solution, given by[9]

$$C(z,t) = C_0 \mathrm{erfc}\left(\frac{z}{2\sqrt{D_{\mathrm{Ag}}t}}\right), \tag{3}$$

where C_0 is concentration of silver in the salt bath.

Equation (3) indicates that concentration of silver in ion exchange process exhibits a complementary error function. The propagation characteristics for this highly asymmetric profile have been determined by the numerical integration of the normalized mode dispersion equation. Here we use these analytical results to fit our experimental data in order to link the process and the device parameters.

Figure 1 shows the relationship between the effective diffusion depth d and the square root of the diffusion time for samples ion exchanged at 335 °C. The effective diffusion depth d was determined from $\Delta n(d)/\Delta n(0) = \mathrm{erfc}(1) = 0.157$[10], $\Delta n(d)$ and $\Delta n(0)$ are the refractive index change at the depth d and at the surface,

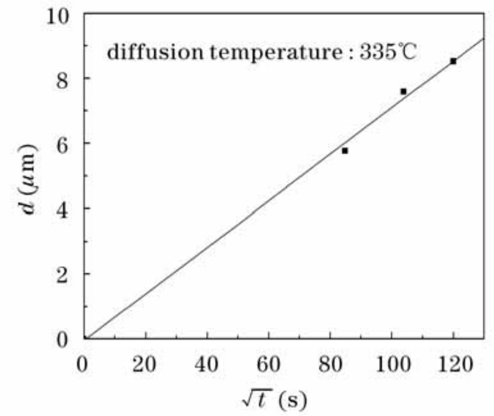

Fig. 1. Variation of effective depth versus the square root of diffusion time.

respectively. Figure 1 indicates that the longer the ion exchange time, the deeper the waveguide. A linear relation was obtained. It is known that the effective diffusion depth d can be expressed by

$$d = 2\sqrt{Dt}, \tag{4}$$

where D is the effective depth coefficient and t is diffusion time. From the slope of the straight line in Fig. 1, the estimated effective diffusion coefficient D at temperature 335 °C is found to be 1.275×10^{-15} $\mathrm{m^2/s}$.

The equilibrium at the melt-substrate interface was investigated in order to obtain an experimental relationship between the maximum refractive index change and the silver concentration in the salt melt. The experimental data are showed in Fig. 2. As expected, the effective refractive indices increase with $AgNO_3$ concentration, and within the investigated concentration range a linear dependence between refractive index change and silver concentration in the melt is found.

To estimate the variation of the diffusion coefficient D with temperature T, three batches of waveguides were fabricated at 335, 345, 355 °C, respectively. The diffusion coefficients at different temperatures were estimated using the calculated effective depth. The variation of D with T is given by an Arhenius type relation[11] $D(T) = D_0\mathrm{e}^{-\Delta H/RT}$, where ΔH is activation energy, D_0 is a pre-exponential factor, and R is the gas constant (8.314 $\mathrm{J\cdot K^{-1}\cdot mol^{-1}}$). In Fig. 3, $\ln(D)$ is plotted as a function of the inverse of the temperature T. From the linear fit of the experimental data in Fig. 3, we obtained $D_0 = 5.132\times10^{-3}$ $\mathrm{m^2/s}$ and $\Delta H = 1.47\times10^5$ $\mathrm{J\cdot mol^{-1}}$, which is comparable to that obtained in commercial phosphate glass[9]. Because of the exponential relationship between D and T, it is important to exactly control the temperature in ion exchange process.

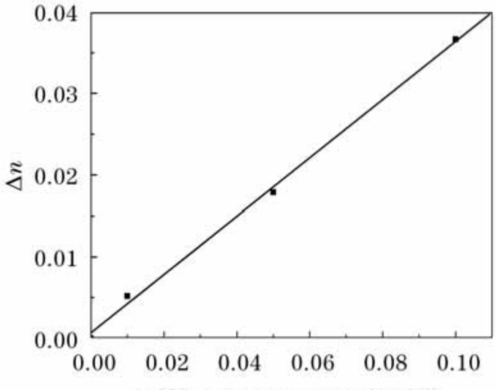

Fig. 2. Refractive index change against the molar concentration of $AgNO_3$ at 335 °C.

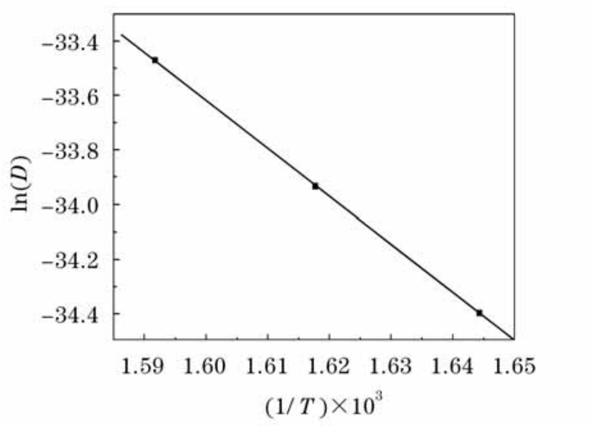

Fig. 3. The relationship between $\ln(D)$ and the inverse temperature $1/T$. Here T is in the unit of K.

In conclusion, a new Er^{3+}/Yb^{3+} co-doped phosphate glass has been applied to ion exchange experiments, which exhibits good spectral properties. We have presented the results of an experimental study of modal characterization of planar waveguides fabricated by Ag^+-Na^+ ion exchange in the glass. With the help of a numerical solution for a graded index (erfc) waveguide, the guiding characteristics were used to estimate waveguide parameters. The results are useful for further fabrication of erbium-doped waveguide lasers and amplifiers by ion exchange technique.

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