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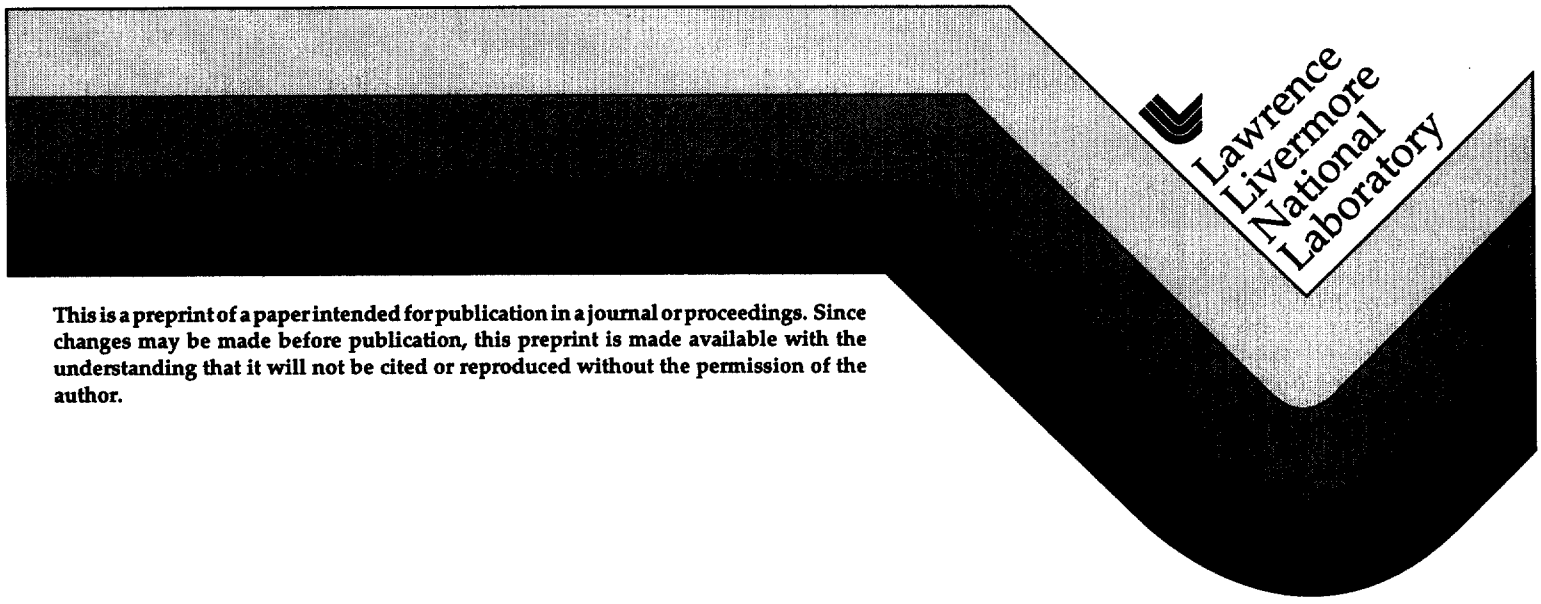

Nd^{3+} AND Yb^{3+} DOPED PHOSPHATE GLASS WAVEGUIDES FABRICATED USING ELECTRIC FIELD ASSISTED Ag^{+} DIFFUSION

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I. INTRODUCTION

Solid-state waveguide lasers offer several attractive features that may make high efficiency and effective thermal management possible. Due to the ability to confine pump light to high intensity over distances much longer than the Rayleigh range, as well as maintaining good overlap between the pump and lasing modes over the entire guiding region, efficient operation with high slope efficiency should be possible, even for quasi-three level laser systems. Since the waveguide region is typically only a few microns of thickness, heat can be extracted efficiently from the structure. The effects of heating are of less significance than in bulk solid-state lasers because mode confinement is maintained by an index of refraction difference, usually much larger than that induced by dn/dT or stress-optic effects. Rare earth doped waveguide laser action has been reported in numerous papers [1-4]. The processes for fabricating waveguides include film deposition methods such as epitaxial growth, RF sputtering, and most recently, thermal bonding of precision finished crystals [5]. In addition, ion implantation, ion exchange in a molten salt and electric field assisted solid film diffusion [6] have been utilized. The ion exchange method remains the simplest, particularly for many common laser glasses that already have mobile ions, and has received considerable attention in recent years. An excellent review is found in reference [7].

Our work has focused on developing process conditions for the fabrication of waveguides in phosphate laser glasses using solid silver film diffusion. These processes are important in determining the overall structure and properties of the guiding region, such as propagation loss, modal profile, and modal overlap between the pump and laser wavelengths. Phosphate laser glass was chosen as the solid state laser medium due to the useful spectroscopic properties of rare earth ions in these materials, as well as the range of material properties and compositions possible.

II. WAVEGUIDE FABRICATION

Fabrication begins with thermally evaporating silver films on both sides of the phosphate glass substrate. A quartz crystal monitor is used to measure the thickness of the silver film during evaporation. The sample is then placed into a furnace where an electric field is applied across the substrate. The diffusion temperature and time are varied from 270 °C to 350 °C and 5 minutes to 45 minutes, respectively. The excess silver is then etched in a solution of nitric acid. A post fabrication anneal may be performed to reduce the overall index of refraction change and increase the diffusion depth.

The typical range of waveguide properties achieved using different process conditions is summarized in Table 1. Malone[4] has previously characterized the properties of the phosphate glass used in our experiments (NIST-1). In this case instead of being neodymium doped, the NIST-1 glass was prepared with 7 wt.% Yb_2O_3 corresponding to an input ytterbium ion density of 6×10^{20} Yb^{3+} ions/cm^3. The designation for the glass melt used in this work was GWO-L1B. Waveguides were prepared by first coating a glass sample substrate (2 inch square by 1 mm thick) with a 200 nm thick silver film. The sample was then cleaved into four pieces and planar waveguides were fabricated under different process conditions. Measurement of the effective indexes using the prism coupling technique is described in Reference [6]. Laser light was coupled into and out of the waveguide by means of a high index prism (n=1.844). The index profile was determined by inverting the wave equation using a WKB analysis. The method is described in detail by Chiang [8]. The smooth index profile was well described by a Gaussian distribution,

$$n(x) = n_{substrate} + \Delta n \, Exp[-(x/d)^2] \qquad (1)$$

where d is the 1/e diffusion depth, Δn is the total change in index, and $n_{substrate}$ is 1.5178 for Yb: phosphate glass and 1.5222 for Nd:phosphate glass (measured at λ = 632.8 nm).

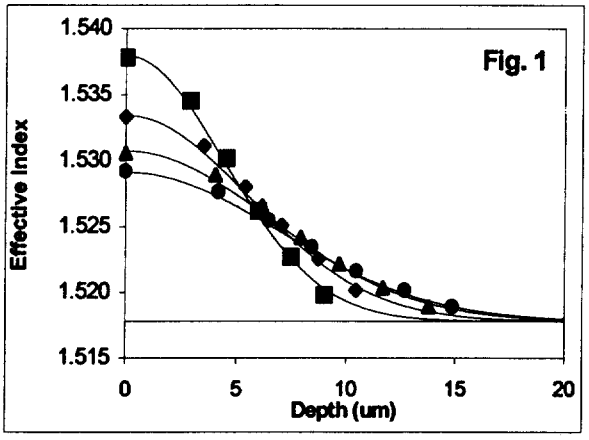
Table I. Summary of parameters for Yb:phosphate glass waveguides

Yb:phosphate glass sample #	1	2a	2b	3a	3b	3c	4
Diffusion temperature, T (°C)	300	300	—	330	—	—	330
Diffusion time, t (min)	15	30	—	5	—	—	15
Applied voltage (V)	15	15	—	15	—	—	15
Anneal temperature (°C)	—	—	300	—	330	330	—
Anneal time (min)	—	—	10	—	10	20	—
Δn	0.014>	0.038	0.027	0.020	0.015	0.013	0.011
Diffusion depth (1/e), d (um)	2.71<	2.71	3.80	6.23	7.86	9.16	9.78
Number of bound modes	2	3	4	5	5	6	6

0.014> indicates slightly greater than 0.014; 2.71< indicates slightly less than 2.71

Table I summarizes the results, an overall decrease in the change in index of refraction, an increase in the 1/e diffusion depth, and additional bound modes for longer

postbake times. Notice that the index change in sample 4 is lower than for sample 3a. This indicates that the silver was depleted before the prescribed 15 minutes were completed. Once the silver source was consumed, thermal migration of the diffused Ag^+ ions occurred in the substrate, reducing the overall surface index of refraction and increasing the diffusion depth. One might expect to achieve a similar index change by annealing sample 3a at 330 °C. Fig. 1 shows the results of successive postbake steps, where the index distribution of Sample 3a is approaching that of Sample 4.



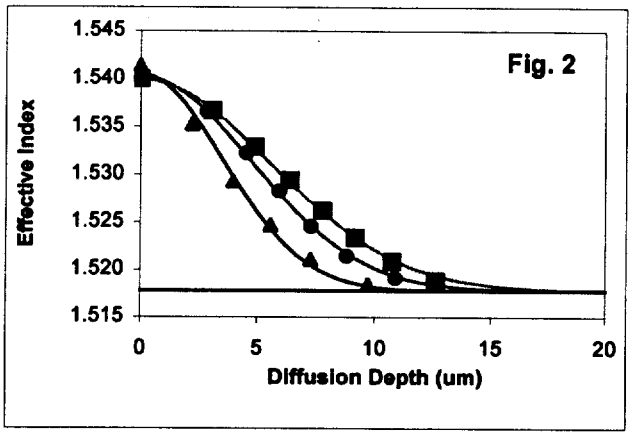


Fig. 1. The profiles are as follows: Square: Sample 3a; diamond: Sample 3b; triangle: Sample 3c; circle: Sample 4. The bulk index of refraction of the substrate is 1.5178. The general trend of the graded index after annealing is a decrease in Δn and an increase in the 1/e diffusion depth.
Fig. 2 Vary applied voltage for diffusion temperature and time of 300 °C and 30 minutes, respectively. Triangle: 5 V; Circle: 7 V; Square: 15V. For all three cases the thickness of the Ag film, the source for ion diffusion, was approximately 250 nm.

Another set of experiments was performed to determine the effect of varying the applied voltage while keeping constant the diffusion time and temperature. As shown in Fig. 2, the overall index change was approximately the same for the three cases while the 1/e diffusion depth and the number of bound modes increased. Similar results, both experimental and numerical, are reported in Reference [6].

III. LOSS CHARACTERIZATION

The formation of Ag colloids during the fabrication is a problem because of scatter and absorption losses. In our experiments a yellowish tint was observed in glass samples fabricated with diffusion temperatures at or above 300°C. It is well known that this discoloration may indicate the presence of Ag colloids[9]. The glass melt GWO-L1B was prepared without the use of refining agents or antisolorants that possibly participate in the generation of reduced silver through a redox interaction. Indeed, in the earlier work with this glass by Malone[4], silver colloid formation was not noted, and the low loss exhibited by the resultant waveguides indicates colloidal silver was probably not present in any significant amount. However, it should be noted that, in this case, visual detection of any yellow discoloration may have been difficult since neodymium-doped variant of this glass was employed.

Loss is an important issue in determining performance characteristics for waveguide lasers. We have estimated the loss in our waveguides to vary from 0.71 dB/cm to 0.99 dB/cm using a two-prism measurement technique, a variation on the three-prism method [10]. Two prisms are held in contact with the waveguide surface by index matching oil. A HeNe laser beam is focused into the first prism and the power of the output light from the second prism, a distance z from the first, is recorded by a photodiode. The exponential loss coefficient α (dB/cm) is then calculated from the following equation: $P_{meas} = P_{ref} \exp(-\alpha z/4.34)$. The reference power P_{ref}, is taken to be the value at the smallest prism separation. The second (output) prism is moved a small distance and another measurement is made. The coupling efficiencies of both prisms are assumed to be the same because large deviations from the exponential loss behavior were not detected (Fig. 3).

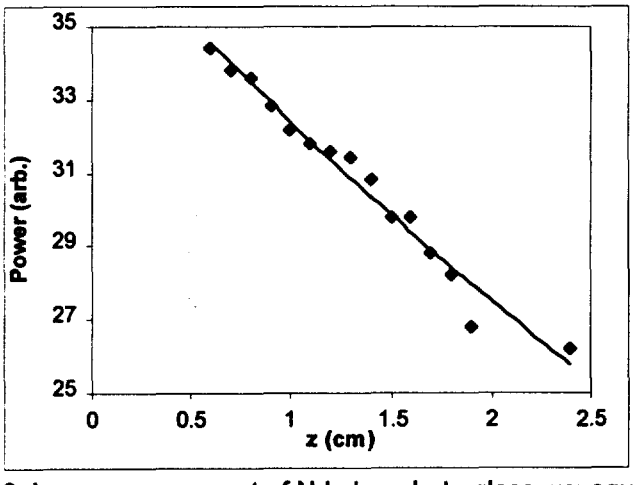


Fig. 3 Loss measurement of Nd:phosphate glass waveguide.

Using the Lorentz-Lorenz equation [11], one can obtain a relationship between the change in refractive index and the Ag concentration diffused into the substrate. The electronic polarizability is given by

$$\alpha = \frac{3}{4\pi N}\left(\frac{n^2 - 1}{n^2 + 1}\right) \tag{2}$$

where n is the index of refraction and N is the number density. Assuming a one to one exchange of silver for sodium ($N_{Ag} = N_{Na}$), we can define a change in polarizability

$$\Delta\alpha \equiv \alpha_{Ag} - \alpha_{Na} = \frac{3}{4\pi N_{Ag}}\left(\frac{n_f^2 - 1}{n_f^2 + 1} - \frac{n_i^2 - 1}{n_i^2 + 1}\right) \tag{3}$$

where n_f and n_i are the final and initial indexes of refraction, respectively. Defining $\Delta n = n_f - n_i$, and approximating $\Delta n << n_i, n_f$, the following equation results:

$$\Delta\alpha = \left(\frac{9n_i}{2\pi N_{Ag}\left(2+n_i^2\right)^2}\right)\Delta n \tag{4}$$

All values in Eq. (4) are known: n_i is 1.5178 (at λ = 632.8 nm) and the electronic polarizabilities for Na and Ag are obtained from Ref. [12]. Rewriting the equation into a compact form with units of weight percent, a linear relationship between the index of refraction and the diffused Ag concentration results,

$$\Delta n = 0.0026 N_{Ag}[\text{wt.\%}] \tag{5}$$

Experimental data is in close agreement with the theoretical result obtain in Eq. 5 [13]. Electron microprobe analysis was performed to determine the Ag concentration in the waveguides and to correlate this result to the graded index distribution using (5). The theoretical result in Fig. 4 is obtained by using the measured index profile which is best described by (1) and using (5) to find the silver concentration as a function of depth. Due to rounding of the sample edge during preparation, the silver concentration at the surface could not be clearly determined. The data in Figure 4 is shifted by several microns to reflect that measurements were made away from the true edge of the waveguide. The microprobe analysis was done to confirm silver diffusion into the phosphate glasses and that the depth of the diffusion was in agreement with calculated results.

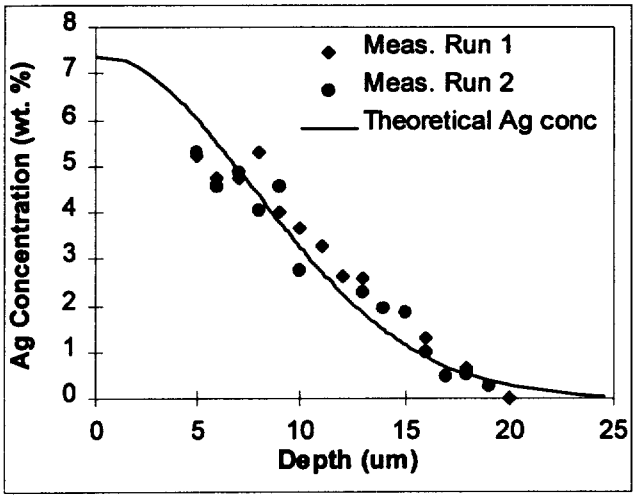


Figure 4. Electron microprobe analysis on a Nd:phosphate glass waveguide with a measured 1/e depth of 11 um and a Δn of 0.018.

IV. CONCLUSION

In conclusion, we have studied electric field assisted Ag ion exchange in Nd and Yb-doped phosphate glasses to understand the role of diffusion temperature, time, and

electric field during waveguide fabrication. Understanding the fabrication process allows one to produce waveguides of prescribed parameters determined for optimal lasing characteristics. The high index changes result in large numerical apertures (NA), which are preferable for diode pumping schemes. Lasing can be theoretically achieved with the current losses in our waveguides, but lower losses, typically on the order of 0.1 dB/cm, are preferable. We are currently building a diode pumped Yb:phosphate glass waveguide laser with both planar and channel guiding regions.

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