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Erbium-doped waveguide amplifiers fabricated using focused proton beam writing

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Buried channel waveguides were fabricated in $Er^{3+}-Yb^{3+}$ codoped phosphate glasses using focused proton beam writing. Proton ion doses in the range of $10^{14}-10^{15}$ ions/cm^2 and 2.0 MeV energy were used. The waveguides were located 38 μm below the substrate surface and are in excellent agreement with the transport and range of ions in matter simulation. The waveguide properties were measured, and the fluorescence spectra and optical gain of the waveguides were characterized. The maximum net gain of the waveguide amplifiers at 1.534 μm wavelength was measured to be ~1.72 dB/cm with 100 mW pump power at 975 nm wavelength. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1644922]

Erbium-doped waveguide amplifiers have attracted much attention recently for use in the 1.5 μm wavelength range, because of their potential to be integrated with pump lasers and other waveguide devices. Different fabrication techniques such as ion exchange,[1] rf sputtering,[2] sol gel,[3] plasma-enhanced chemical vapor deposition,[4] and femtosecond laser pulses,[5] have been used to make these Er-doped waveguide devices. As expected, different techniques lead to different forms and qualities of the waveguides. Er-implanted Al_2O_3 waveguide amplifiers have also been reported, and their net gain was 0.58 dB/cm with 9 mW pump power at 1.48 μm wavelength.[6] Ion beam irradiation has also been extensively used to fabricate planar waveguides, and various types of particles have been used, such as protons, helium and other ions.[7] The density and hence the refractive index of the material change accordingly.

Work on planar waveguide fabrication using focused high energy proton (H^+) beam direct writing is mainly restricted to passive materials, such as fused silica[8] and polymethylmethacrylate (PMMA).[9] Optical waveguides fabricated by proton beam irradiation in fused silica and by femtosecond laser pulses in phosphate glasses have been characterized in the visible wavelength only.[10,11] Although mode profiles of proton beam irradiated waveguides in fused silica operating at 1.5 μm wavelength were studied afterwards, the focus was on the passive waveguiding effect,[12] and no investigations of active waveguides using focused proton beam writing (PBW) have been reported. Several studies have been carried out on the optical effects in He^+ implanted $Er^{3+}-Yb^{3+}$ codoped phosphate glasses,[13,14] however, the spectroscopic properties and gain characteristics of active waveguides were not mentioned.

In this letter, we report on the use of focused PBW to fabricate buried channel waveguides in $Er^{3+}-Yb^{3+}$ codoped phosphate glasses. The ion doses and energy used were in the range of $10^{14}-10^{15}$ ions/cm^2 and 2.0 MeV, respectively. The waveguide end face was measured using a tapping mode atomic force microscope (AFM) to assess the region modified after writing and before thermal annealing. The photoluminescence properties and the optical gain of the waveguide amplifiers were also characterized.

The substrates used were phosphate glasses codoped with different value of Er and Yb ions (substrate B: 2.3 wt% Er_2O_3, 3.6 wt% Yb_2O_3; substrate A: 4.0 wt% Er_2O_3, 3.0 wt% Yb_2O_3). The bulk glasses were cut into slices of 10.0 $\times$8.0 mm^2 and were edge polished before writing. In focused PBW, the incident beam modifies the refractive index of the phosphate glasses along the irradiated pathways,[15] and buried channel waveguides form. PBW was carried out using the proton beam writer facility at the Center for Ion Beam Applications, National University of Singapore.[16] Figure 1

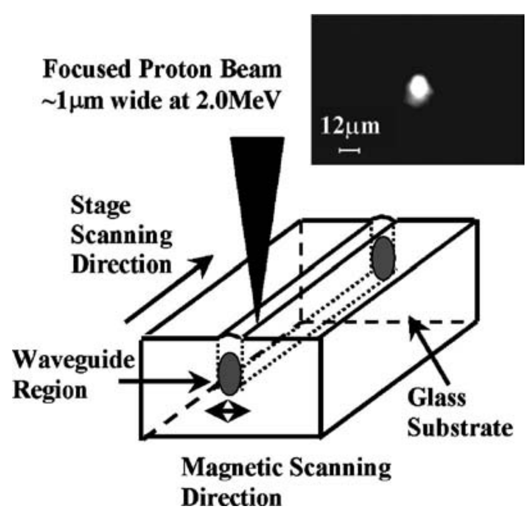

FIG. 1. Schematic diagram of the focused PBW fabrication process. A combination of stage scanning and magnetic scanning was used to write the waveguides.

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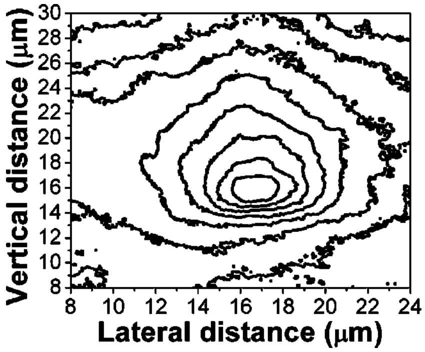

FIG. 2. Contour plots at the end face of a PBW waveguide (ion dose ~2 $\times 10^{15}$ ions/cm^2). Eight contour levels are used, and each is spaced ~2.9 nm.

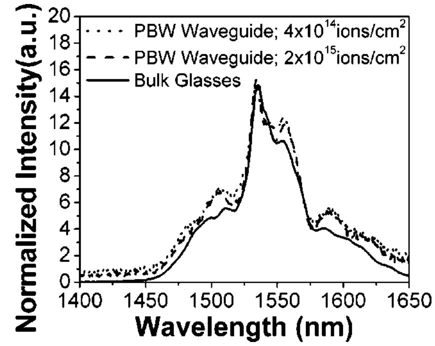

FIG. 4. Fluorescence and ASE spectra of bulk glasses and PBW waveguides.

shows schematically the optical waveguide fabrication process. A 2.0 MeV proton beam with ion doses in the range of 10^{14}–10^{15} ions/cm^2 and focus spot size of ~1 μm were used to produce the direct-write buried waveguides. The inset in Fig. 1 depicts an elliptical mode profile of the waveguide measured at 1.55 μm wavelength in substrate A using end-fire coupling. The ion dose used was 2×10^{15} ions/cm^2.

Postannealing experiments were carried out to decrease propagation loss. Defects from both electronic and nuclear interaction of the incident ions and substrate atoms are reduced.[17] The waveguides were annealed between 150 and 400 °C for 0.5 h, and propagation losses before and after annealing were determined from insertion loss measurements by subtracting Fresnel losses and input coupling losses at 1.3 μm. The experiment was carried out at 1.3 μm in order to avoid strong Er^{3+} absorption at 1.5 μm. The small signal gain at 1.534 μm was measured by pumping the waveguide with a 975 nm laser diode. The input signal source was a HP8161A tunable laser, and a 980 nm/1550 nm wavelength division multiplexing coupler was used to combine both the signal and pump light. An optical spectrum analyzer was used to record the optical gain and the amplified spontaneous emission (ASE) spectrum.[1]

Figure 2 shows contour lines of swelling at the waveguide end face profiled using an AFM, with the lateral distance of the waveguide aligned parallel to the slow scan axis of the AFM. The AFM image was also flattened using a low-order polynomial fit. Pear shape volume dilatation is observed, and maximum surface swelling of 23 nm is obtained for an ion dose of 2×10^{15} ions/cm^2 at 2.0 MeV. From the AFM image, the horizontal size of the waveguide core is estimated to be ~8 μm, which is attributed to the magnetic scan size of ~5 μm, the beam spot size of ~1 μm and lateral straggling of ~1.6 μm [transport and range of ions in matter (TRIM) simulations]. The vertical dimension of the waveguide is due to the Bragg peak.

Figure 3 shows TRIM simulations of the oxygen and phosphorus vacancies as a function of the penetration depth in the glasses. High energy protons cause impact damage in the form of phosphorus and oxygen vacancies at the end of ion penetration, which increases the refractive index to some degree and hence the waveguiding effect. From the simulation, the protons are estimated to penetrate 38.7 μm below the substrate surface.[18] Channel waveguides 8 μm wide, measured experimentally, were located ~38 μm below the surface, and this is in excellent agreement with the TRIM simulation results.

Figure 4 compares an ASE spectrum of the optical waveguides and a fluorescence spectrum of bulk glasses (substrate A). Each spectrum is similar to the other, indicating that the spectroscopic property of bulk glass is unaffected by the waveguide fabrication process. The peak wavelength is around 1.534 μm, and is due to the transition of $^4I_{13/2}$ to the $^4I_{15/2}$ level in Er^{3+}. The full width at half maximum (FWHM) is ~45 nm. The FWHM measured is consistent with the value of fluorophosphate glasses, but far larger than those measured in Er^{3+}-doped Ge–P silicate glasses.[19] A similar result was also obtained for substrate B. Table I shows a comparison of the measured small signal optical gain in the waveguide amplifiers fabricated using different ion doses. The input signal power was <-25 dBm and the

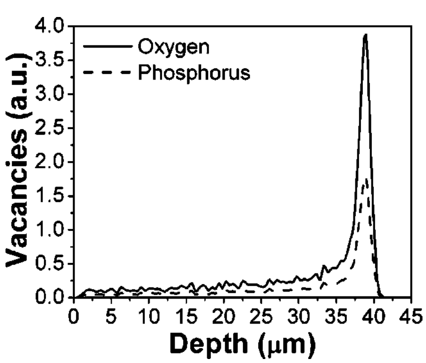

FIG. 3. Distribution of oxygen and phosphorus vacancies in phosphate glasses as a function of the penetration depth using TRIM simulation. The proton energy used is 2.0 MeV.

TABLE I. Net gain of PBW waveguide amplifiers fabricated using different ion doses.

Ion dose (ions/cm^2)	Net gain of substrate A (dB/cm)	Net gain of substrate B (dB/cm)
4×10^{14}	0.24	0.52
5×10^{14}	0.44	0.86
6×10^{14}	0.91	1.27
7×10^{14}	1.24	1.54
8×10^{14}	1.45	1.72
9×10^{14}	1.33	1.65
1×10^{15}	1.25	1.51
2×10^{15}	1.16	1.38
3×10^{15}	0.75	1.00

pump power used was 100 mW. When the ion dose is low the optical gain is also low. For low ion dose, the change in refractive index is too small to support a well confined optical mode at 1.5 μm wavelength. At very high ion dose the gain is also low. This is because the refractive index change in PBW waveguides is strongly ion dose dependent. A low ion dose will often raise the change in index to some degree, whereas a high dose will lower this value.[20] The waveguiding effect at high ion dose was monitored using end-fire measurement. For ion dose higher than 1×10^{16} ions/cm^2, no confinement of light within the channel is observed at 1.5 μm wavelength. In that case, we believe that the threshold dose was exceeded and that an ''optical barrier'' of low refractive index built up at the end of the ions' track in the modified region. The fabrication of planar waveguides in phosphate glasses using ion implantation (with doses $\geqslant 1\times10^{16}$ ions/cm^2) previously reported was based on this concept of optical barrier,[13,14] in which the region between this barrier and the glass surface is surrounded by regions of lower refractive indices.

In our work an annealing temperature of 220 °C was used due to the relatively weak P–O bond structure compared to that of fused silica. The average propagation loss of the annealed waveguides was reduced from ~3.2 to ~0.8 dB/cm, and the maximum net gain increased to ~1.72 dB/cm for an annealed waveguide (ion dose $\sim 8\times10^{14}$ ions/cm^2 in substrate B). In general, the optical gain in substrate B is higher than that in substrate A for similar ion dose, and is due to the Yb–Er concentration ratio.[21] By optimizing the ion dose, the annealing conditions and the Yb–Er ratio, waveguide amplifiers with higher net gain should be possible.

In conclusion, buried channel waveguides formed by focused PBW were demonstrated in Er^{3+}–Yb^{3+} codoped phosphate glasses. Single 2.0 MeV proton beam energy and ion doses in the range of 10^{14}–10^{15} ions/cm^2 were used. Waveguides 8 μm wide formed ~38 μm below the substrate surface. The fluorescence and ASE spectra of the bulk glasses and waveguides were measured, and were found to be similar to each other. The maximum net gain of the waveguide amplifiers at 1.534 μm signal wavelength was ~1.72 dB/cm with 100 mW pump power at 975 nm wavelength. Focused PBW is shown to be a suitable technique for making erbium-doped waveguide amplifiers, and it offers great versatility in the fabrication of optical devices and circuits. Further work is currently in progress on investigation of the postannealed waveguide end faces using an AFM and recovery of the refractive index profile of the waveguides using the propagation-mode near-field method, which will give us a better understanding of the waveguide formation mechanism.

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