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Monomode optical planar and channel waveguides in Yb^{3+}-doped silicate glasses formed by helium ion implantation

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ABSTRACT

Optical planar and channel waveguides in Yb^{3+}-doped silicate glasses are fabricated by triple-energy helium ion implantation at a total dose of 6.0×10^{16} ions/cm^2. The dark mode spectroscopy of the planar waveguide was measured using a prism coupling arrangement. The near-field mode profiles of the planar and channel waveguide were obtained with an end-face coupling system. The refractive index profile was reconstructed by the intensity calculation method. The results indicate that a refractive index enhanced region as well as an optical barrier has been created after the beam process. After post-implantation treatment at 260 °C for 1 h, the channel waveguides possessed a propagation loss of ~1.2 dB/cm. The acceptable guiding properties suggest that further waveguide lasers may be realized on the He-implanted Yb^{3+}-doped silicate glass waveguides.

1. Introduction

A class of materials like Yb^{3+}-doped silicate glasses are suitable for fabricating diode-pumped, tunable and ultrafast high-power laser sources. This is due to their broad absorption and emission bandwidths and low thermal loading properties. Recently, they have also received more and more attention owing to their high nonlinearity, which is suitable for optical switching. In addition, since there are only two manifolds in the Yb^{3+} energy level scheme, the $^2F_{7/2}$ ground state and $^2F_{5/2}$ excitation state, it is commonly believed that upconversion, excited state absorption and concentration quenching have no effect on it. Compared with Yb^{3+}-doped phosphate and borate glasses, Yb^{3+}-doped silicate glasses have their own benefits such as stable physical and chemical properties, low cost, and possible fused coupling with silica fibers. Therefore, in the light of these advantages, the Yb^{3+}-doped silicate glass has a potential value as a laser waveguide [1–5].

The optical waveguide plays a critical role in the modern photonic system as a basic element. It can confine the light propagation in one or two dimension (1D or 2D), i.e., in planar or channel configuration, reaching a much higher optical intensity inside the waveguide layers than in the bulk. As a result, waveguide lasers usually show a lower pump threshold and a higher slope efficiency compared with corresponding bulk lasers. It is especially important for Yb^{3+}-doped laser materials, because the quasi-three-level nature requires a relatively high pump intensity for efficient laser operation. Consequently, the fabrication of active waveguides on laser materials is the first step to develop novel, compact, and cost-effective integrated lasers. In addition, if the physical shapes and correlated modal profiles have suitable dimensions, 2D waveguides can be easily connected to optical fibers with a high coupling efficiency for construction of integrated photonic systems [6–9]. To produce high-quality optical waveguides in glass substrates, several techniques have been investigated, such as ion exchange [10], laser writing [11] and ion implantation [12,13]. Ion implantation, as one of the most accepted methods for fabricating waveguide structures in most optical materials, has been proven to be an efficient method owing to its superior controllability and reproducibility compared with other techniques. In the research area of ion-implanted waveguides, accelerators are more often used because they offer high energies of specific implanted ions at acceptable doses. The implanted ions, normally with positive charges, are extracted out from the sources, experiencing acceleration and mass/energy selection, and bombarded into the target materials by the beam scanning technique, by which uniform irradiation is ensured over the sample surface. In most cases, the optical barrier refers to low refractive index layers buried inside the substrate generated by the stopping

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of implanted-ions; therefore, the waveguide structure can be formed between the sample surface and the optical barrier. This technique offers accurate controlling of the refractive index profiles of the waveguides by selecting diverse ion species, energies, and fluences. In addition, it does not depend on the chemical properties of the target materials, which makes it unique and applicable for many materials. Therefore, the combination of excellent laser performance of Yb^{3+}-doped silicate glasses and effective waveguide technology of ion implantation is one promising solution to the realization of high-power integrated lasers with a stable output. In this work, we fabricated, for the first time to our knowledge, planar and channel waveguides in Yb^{3+}-doped silicate glasses by He^+ ion implantation.

2. Experiments

The Yb^{3+}-doped silicate glasses of SiO_2–B_2O_3–Al_2O_3–Na_2O–La_2O_3–Y_2O_3 with 2.0 mol% Yb_2O_3 were prepared under a high temperature condition by the melt-quenching method by our group. The samples, with a size of $10.0 \times 10.0 \times 2.0\ mm^3$, were optically polished and cleaned. Its refractive index is 1.6166 at 632.8 nm and fluorescence lifetime is 1.05 ms at 1010 nm. A thick-film positive photoresist (BP-218) was spin-coated onto the sample surface for 50 s at 5000 r/min, forming a photoresist mask with thickness of ~5.0 μm. After the standard lithographic processing, a series of open stripes with a width of 7.0 μm (unshielded) and a separation of 43.0 μm (shielded) between the adjacent channels were patterned on the sample surface. Owing to the thermal treatment, the cross-sections of the mask stripes were strongly wedged. In order to produce a broad barrier to avoid tunneling losses, with this mask the multiple He^+ ion implantations at energies of (450+500+550) keV and doses of $(2.0+2.0+2.0) \times 10^{16}\ ions/cm^2$ were performed by using an implanter at room temperature at the Institute of Semiconductors, Chinese Academy of Sciences. Owing to the block effects of the wedged edges of the photoresist mask, the channel waveguides were constructed in the unshielded regions of the sample surface with trapezoid boundaries at their cross-sections. In addition, about one-third part of the sample surface was uncovered with any mask to allow planar waveguide fabrication in the Yb^{3+}-doped silicate glasses. Fig. 1 sketches the schematic of the fabrication process of the waveguides in the Yb^{3+}-doped silicate glass samples and the scanning electron microscopy (SEM) of the channel waveguide sample cross-section, and the photo of the implanter. To reduce the color centers and defects created during the implantation process, the sample was annealed at 260 °C for 1 h in air.

We used the *m*-line technique to measure the dark-mode spectroscopy of the planar waveguide through a prism coupler (Metricon 2010, USA) with a resolution better than 0.0002. According to the *m*-line curve, the refractive index profile was reconstructed by the intensity calculation method. The near field profiles of the planar and the channel waveguides were measured through an end-face coupling system. During the measurement, a microscope objective lens (×25) focused the light beam into the waveguide to excite the guided modes, and another microscope objective lens (×25) collected the light from the output facet of the sample, which was imaged onto a CCD camera. The propagation losses of the channel waveguides were determined by a Fabry–Perot resonance method, as shown in Fig. 2 [14]. A He–Ne laser with a wavelength of 632.8 nm was used as the light source during above experiments.

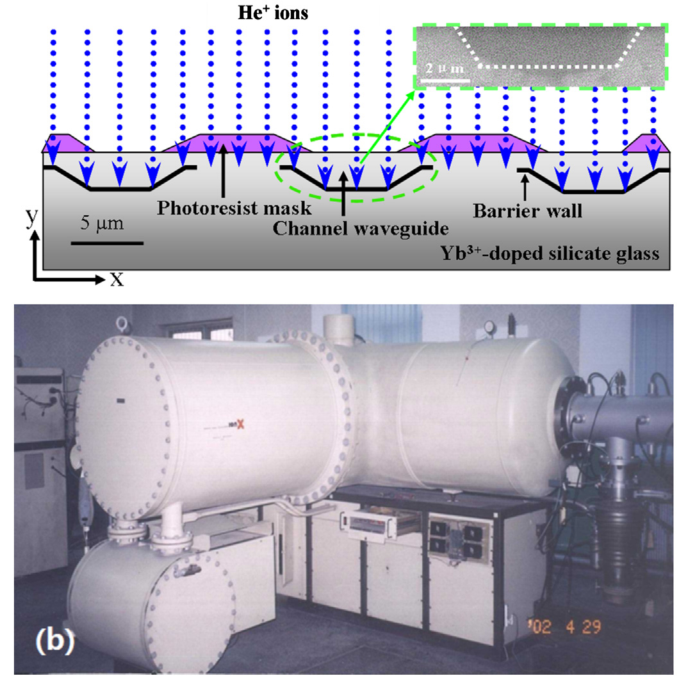

Fig. 1. (a) Schematic of the waveguide fabrication process in the Yb^{3+}-doped silicate glass and the inset is the SEM of the channel waveguide cross-section; and (b) photo of the implanter.

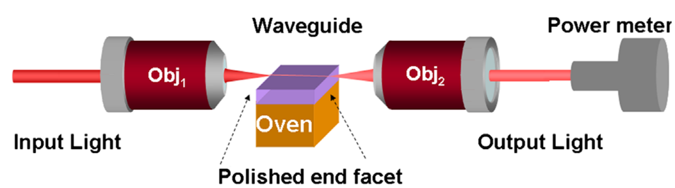

Fig. 2. Schematic of the experimental setup for loss measurement through the Fabry–Perot resonance method.

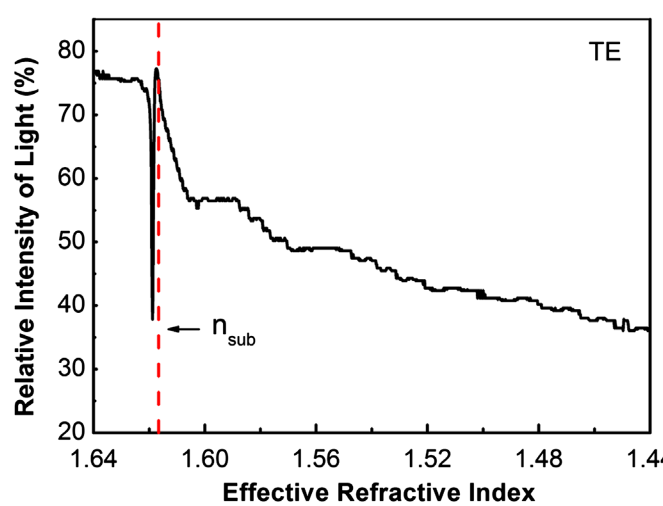

Fig. 3. Measured relative intensity of light (TE polarized) reflected from the prism versus the effective refractive index of incident light for the Yb^{3+}-doped silicate glass waveguide formed by (450+500+550) keV He^+ ion implantation at a dose of $(2.0+2.0+2.0) \times 10^{16}\ ions/cm^2$ at room temperature.

3. Results and discussion

Fig. 3 shows the TE dark modes spectra of the planar waveguide in the Yb^{3+}-doped silicate glass formed by (450+500+550) keV helium ion implantation at a dose of $(2.0+2.0+2.0) \times 10^{16}\ ions/cm^2$ after the annealing treatment. The refractive index of the substrate was also marked for comparison. When the light was coupled into the waveguide region, a lack of reflected light