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Ridge waveguides in Yb$^{3+}$-doped silicate glass fabricated by combination of proton implantation and femtosecond laser ablation

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Abstract

Ridge waveguides were fabricated in Yb$^{3+}$-doped silicate glass by proton implantation combined with the femtosecond laser ablation. The Yb$^{3+}$-doped silicate glass were implanted by H$^+$ ions with the double-energy (470 keV + 500 keV) at a total dose of $3 \times 10^{16}$ ions cm$^{-2}$ for the formation of planar waveguides. After annealing at 260 $^\circ$C, the double-line modification tracks, which provide lateral confinement of light to form ridge waveguide structures, were inscribed on the surface of sample with 3 $\mu$m pulse laser energy, 50 $\mu$m s$^{-1}$ scan speed, and 25 $\mu$m separation. The vacancy distribution of the original planar waveguide structure induced by the proton implantation was numerically calculated by the SRIM 2013. The near-field intensity distribution of the waveguide was measured by the end-face coupling system, which shows that the light can be well confined in the ridge waveguide. The micro-fluorescence features have been found well preserved in the waveguide region. This work indicates that the ridge waveguide fabricated by laser ablation assisted proton implantation in Yb$^{3+}$-doped silicate glass has an important potential as an active waveguide device in optical fiber communication and all-optical communication.

1. Introduction

Integrated optics offers chip-level platforms, including a variety of compact, low propagation loss and diffraction-free photonic devices with different functions [1–5], and promotes the rapid development of all-optical networks. Optical waveguide, as the most basic element of integrated optics, plays a critical role in data transmission, device cascading, etc. With the emergence of a large number of passive waveguide devices [6–9], active gain waveguide devices [10–12] as chip light sources have become a key and urgent need for the realization of integrated optics. Compared with the traditional bulk active gain devices, the waveguide structures confine light to a range of microns or even sub-microns for waveguide lasers or waveguide amplifiers, resulting in high pump optical intensities in the waveguides region. In this way, with the optimization of laser cavity parameters, the threshold value of the pump can be effectively reduced and the slope efficiency can also be improved. Therefore, the preparation of waveguide structures on active media without reducing original laser gain characteristics is the precondition of realizing waveguide lasing or waveguide optical amplification. Thus, the appropriate laser media and waveguide preparation methods are the key to obtain high-performance active gain devices.

In recent decades, many kinds of outstanding solid-state laser materials [13, 14] have emerged, promoting the development of laser technology continuously. Among these laser materials, Yb$^{3+}$-doped silicate glass is the focus issue of near-infrared materials research [15] owing to its excellent fluorescence, high pump absorption efficiency and wide emission spectrum range. Furthermore, Yb$^{3+}$-doped silicate glass also has high thermal conductivity coefficient and laser damage threshold. It is worth mentioning here that highly doped Yb$^{3+}$ ions are allowed without obvious concentration quenching and excited state absorption, which benefits from its simple...
electronic energy level (ground state $^2F_{7/2}$ and excited state $^2F_{5/2}$). Therefore, Yb$^{3+}$-doped silicate glass is a favorable medium for fabrication of compact active waveguide device. In addition, the long fluorescence lifetime (about 1 ~ 2 ms) of Yb$^{3+}$-doped silicate glass provides better conditions for the realization of Q-switched laser and ultrashort pulse laser amplification. In view of these advantages, the fabrication of waveguide devices on Yb$^{3+}$-doped silicate glass has great potential in integrated optics.

As of yet, several fabrication techniques, including ion implantation [16–19], ion exchange [20] and ultrafast laser inscription [21–23], have been successfully used to form high-quality optical waveguides in different materials. Among these techniques, ion implantation, which can precisely control the energy and dose [24] during processing, makes the waveguide structure flexible and adjustable. In addition, in the region of ion irradiation, the optical properties of the substrate can be well preserved [25]. Therefore, ion implantation has become a common method for the preparation of planar waveguides. In practice, the two-dimensional waveguide (ridge/strip waveguide) can confine the guided mode in two directions, which exhibits several advantages, such as higher light intensity in the waveguide, flexible adjustment of guided mode in the horizontal direction with respect to the one-dimensional planar waveguide. More importantly, 2D waveguides are more convenient to couple with conventional waveguides such as optical fibers, which is due to more similar modes. In other words, higher mode overlap often leads to lower connection loss. Therefore, it is necessary to fabricate two-dimensional waveguide devices for highly efficient interconnection of various devices in integrated optical system. Recently, ultrafast laser ablation assisted ion implantation technology has become an ideal candidate for ridge waveguide preparation [26–28]. In the process of femtosecond laser irradiation on materials, the laser energy is focused into a very small volume to produce nonlinear absorption, followed by the local material removal. During the whole process, the material outside the focus region were not damaged due to the advantage of ultrafast interaction of femtosecond laser. Therefore, we employ femtosecond laser ablation technique to realize the 2D waveguide structure in the process of waveguide fabrication. Compared with the traditional 2D waveguide preparation method, such as mask assisted ion implantation, the 2D waveguide structures prepared by femtosecond laser ablation assisted ion implantation can adjust different size parameters without re-preparing the mask again, and only need to adjust the relative position of laser and sample. Even, femtosecond laser ablation can easily produce complex structures such as curved two-dimensional waveguides. Therefore, the fabrication method combining ion implantation and femtosecond laser is simple, fast and efficient, and suitable for most materials.

In this work, ridge structure waveguides in Yb$^{3+}$-doped silicate glass have been realized by laser ablation assisted proton implantation technology. As far as we know, it is the first time that this hybrid waveguide preparation technology has been applied to Yb$^{3+}$-doped silicate glass successfully. The guided-mode property of ridge waveguide is experimentally investigated in detail. The mode field is confined not only by the ion implantation effect in the vertical direction, but also by the laser ablated air grooves in the horizontal direction. Thus, the guided single-mode is realized at 976 nm, which is beneficial to improve the pump light intensity and reduce the pump threshold in the field of waveguide laser and waveguide amplifier. The results of micro-fluorescence spectra in the waveguide region show that the laser characteristics of the substrate are well preserved after ion implantation and femtosecond laser ablation. These characteristics provide a guarantee for the realization of active waveguide devices in Yb$^{3+}$-doped silicate glass in the future.

2. Experiments

The Yb$^{3+}$-doped silicate sample (2 mol% Yb$_2$O$_3$, XIOPM, CAS) used in this work was cut with the size of 10 mm $\times$ 8 mm $\times$ 2 mm. For efficient ion implantation and subsequent observation under the microscope, the sample was optically polished and carefully cleaned.

The whole waveguide fabrication process is divided into two steps. The first step is planar waveguide formation by double energy (470 keV + 500 keV) proton implantation. Figure 1(a) shows that 470 keV H$^+$ ions ($1 \times 10^{16}$ ions cm$^{-2}$) were firstly irradiated onto the biggest facet (10 mm $\times$ 8 mm) of the Yb$^{3+}$-doped silicate glass at Institute of Semiconductors, CAS. It is worth mentioning that a second 500 keV H$^+$ ions ($2 \times 10^{16}$ ions cm$^{-2}$) implantation was subsequently performed on the sample, which can produce a broadband barrier and avoid tunnel losses.

In order to prevent thermal effect, the low proton beam current densities were adopted during the double-energy implantation process, respectively. The thickness of the planar waveguide was about 5 μm after the double energy proton irradiation. Thereafter, the planar waveguide was annealed in air for 1 h at a temperature of 260 °C to reduce the propagation loss and improve the guided mode property.

The second step is to construct the ridge structure by ultrafast laser micromachining. Figure 1(b) shows the laser ablation experimental setup. A Ti: Sapphire fs laser system (Spitfire, SP), which can deliver pulses with repetition rate of 1 kHz, central wavelength of 808 nm and pulse duration of 150 fs, was used in the experiment.
The sample was fixed on a 3D ultra-precision positioning stage driven by a computer. The femtosecond laser was delivered to the top surface of the implanted planar waveguide by a 20 × objective with a numerical aperture of 0.42. A 1/2 λ plate and a polarizer were employed to control the pulse energy irradiated to the sample. It should be point out the femtosecond laser energy on the Yb3+ -doped silicate glass sample mentioned below was measured after the focusing lens. During the processing of the ridge waveguide, the laser energy was kept at 3 μJ.

The velocity of femtosecond laser ablation was set to 50 μm s⁻¹, allowing also for moderate processing efficiency and the achievement of enough crater depth (at least equal to or close to the waveguide thickness of 5 μm). Then, two parallel grooves, which can provide a horizontal confinement of light propagation, were ablated by the laser scanning with separation of 25 μm. In this way, a 2D confinement of light propagation was formed, and the ridge waveguide have been successfully realized in the Yb3+-doped silicate glass sample.

An optical transmission microscopy (OTM) with a CCD was employed to investigate the morphology of the ridge structure constructed by the laser ablation. The experimental setup of near-field mode measurement was shown in figure 2, including a 976 nm laser diode (LD), 25 × coupling and collecting lenses (marked as Obj1 and Obj2 in figure 2), and a CCD camera for recording light intensity. In this face-end coupling setup, waveguides were illuminated by a 976 nm laser through the Obj1, and the near-field intensity distributions of the waveguides were collected by the Obj2 and recorded in the CCD camera. In order to adjust flexibly, the waveguide sample, the microscope objectives and CCD were respectively mounted on 6D optical stage.

3. Results and discussion

3.1. Guided-mode Properties
The vacancy distribution of the original planar waveguide structure induced by the (470 + 500) keV H⁺ ions implantation was numerically analyzed by the SRIM 2013 [29]. Figure 3 shows that the vacancy distributions corresponding to 470 keV and 500 keV H⁺ ions implantation conditions, as well as the total vacancy distribution, all of which are functions of depth from the top surface. It can be seen that the depth of the peak value of vacancy distribution corresponding to 500 keV H⁺ ion implantation is greater than that corresponding to 470 keV H⁺ ion implantation. As shown in the black color curve in figure 3, the peak value of the total vacancy distribution is about 0.00013 and the corresponding depth is 5 μm. The results show that the replacement of Na⁺ ion in the sample by H⁺ ion mainly occurs at the end of the H⁺ ion track, which leads to the decrease of local density and refractive index. In this way, an optical barrier is formed in the region of the H⁺ ion deposition. In the process of ion implantation, the implanted ions will deposit energy into the substrate material by two mechanisms [30–35], including atomic inelastic collision and ionization process which destroys the bonds of atoms in the host material. For the implantation of light H⁺ ions into silicate glass, only the ionization-induced...
volume compaction mechanism needs to be considered in the ion implantation trace (waveguide region) [31]. The compaction induced by the ionization process is also mentioned in Ref. 32, and it is easy to saturate at a very low value. Due to the volume compression, the density will increase, which leads to the increase of refractive index [31]. Therefore, it can be said that during the H⁺ ion implantation process mentioned in this paper, the Si–O bonds in the substrate were destroyed by H⁺ ion irradiation, resulting in compression effect, which saturates rapidly at low value. Therefore, the refractive index of the waveguide region increases slightly. With these two refractive index change effects in these two regions, the typical ‘well + barrier’ refractive index distribution was formed, and then light can be well confined in this interlayer by combining with the air cladding. As a result, the planar waveguide have been realized.

In the whole process of laser ablation, as mentioned in section 2, the pulse laser energy was set to 3 μJ, which is just enough to ablate a certain size groove without causing more damage to the waveguide region. Meanwhile, with the laser ablation speed of 50 μm s⁻¹, the mean number of femtosecond laser pulses injected into each point (the diameter of static laser machining point is 3 μm) on the top surface of planar waveguide is ~60, resulting in a groove with a depth of 4.5 μm. The transverse width of ridge waveguide depends on the separation of two adjacent parallel grooves processed by femtosecond pulse laser.

The two grooves separation of the ridge structure was selected as 25 μm in this experiment. Figure 4 shows the optical micrograph of the end-face of the waveguide. The cross-section of the grooves ablated by the femtosecond laser can be observed clearly. The air groove depth is ~4.5 μm, which is close to the thickness of planar waveguide. The inset is the top view of the ridge waveguide, which shows that the two grooves ablated by femtosecond laser are uniform and the width of ridge waveguide is consistent in the longitudinal direction of waveguide. In addition to the refractive index modification caused by ion implantation mentioned above, stress

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**Figure 3.** Vacancy distributions of the planar waveguide corresponding to 470 keV and 500 keV H⁺ ions implantation and the total vacancy distribution.

**Figure 4.** The microphotograph of the end-face of the waveguide. The yellow dotted rectangle represents ridge waveguide region. The inset is the top view image of the sample.
also appears near the two grooves during femtosecond laser ablation, which will increase the density of the material and the refractive index modification.

The near-field intensity distribution was investigated by end-face coupling method. The 976 nm laser was coupled into the ridge waveguide by Obj 1, then collected by Obj 2 and imaged to the CCD camera. Figure 5 depicts the near-field intensity distribution of the ridge waveguide fabricated with two grooves separation of 25 μm. As shown in figure 5, the 976 nm laser can be well confined in the ridge waveguide region and only fundamental mode can be supported in both vertical and horizontal directions. The measured result of the above-mentioned near-field mode profile is in accordance with the structural characteristics of ridge waveguide.

The modification of the refractive index in the ridge waveguide region was estimated by measuring the numerical aperture of the waveguide, The maximum refractive index change \( \Delta n \) was calculated to be \( \Delta n \approx +0.006 \) by using the formula

\[
\Delta n = \frac{\sin^2 \Theta_m}{2n}
\]

where \( \Theta_m \) is the maximum angle of incidence of light that can be reached without changing the transmission power, and \( n = 1.616 \) is the refractive index of the unmodified substrate.

In addition, the propagation loss of ridge waveguide was estimated by insertion loss measurement with the same coupling system mentioned above. It should be pointed out that the 976 nm LD was replaced by a 1053 nm (outside the absorption band of the Yb\(^{3+}\) ions) fiber laser. The transmittance of the coupling lens and the collecting lens are both 90%. The total loss of the 10 mm-long ridge waveguide was 2.7 dB for guiding mode. In consideration of inevitable coupling loss between waveguide and fiber, the propagation loss should be less than 2.7 dB cm\(^{-1}\). The propagation loss is mainly due to scattering from the side walls of the waveguide processed by the femtosecond laser. Further optimization of laser ablation parameters can reduce propagation loss.

3.2. Micro-fluorescence properties

In order to investigate the impact of ion implantation and femtosecond pulse micromachining on the active gain properties of the ridge waveguide region during the fabrication process, the micro-fluorescence measurement was performed in the waveguide region and bulk medium region respectively. A 976 nm LD was used as an excitation source for fluorescence spectra. It is worth mentioning that in the process of fluorescence measurement in waveguide region, the Obj1 depicted in figure 2 is replaced by a 40 \( \times \) microscope objective lens, which can deliver more energy into the waveguide and reduce the impact of the pump excitation of the bulk medium on the measurement. The excited spectra are collected by single-mode fiber (Corning, HI1060) into the optical spectrum analyzer (YOKOGAWA, AQ6370D).

Figure 6 depicts the 976 nm laser excited micro-luminescence emission spectra \((^2F_{5/2} \rightarrow ^2F_{7/2} \text{ transition of Yb}^{3+} \text{ ions})\) of ridge waveguide and substrate, respectively. As we can see, the emission spectrum from the ridge structure region is very similar to that from the bulk medium region in the shape profile, including continuous spectral components ranging from 950 to 1100 nm and the peak value near 1030 nm.

The results show that the fluorescence characteristics of the waveguide region can be well retained, which implies that the Yb\(^{3+}\) ions are weakly or not affected by the implanted ions and the stress caused by laser ablation. There are two reasons for the fact that fluorescence properties of the waveguide region are well...
preserved. One is the low dose value of $H^+$ ions implantation, and the other is the unique outer closed electronic shells of Yb$^{3+}$ ions, which can protect the inner layer electron energy levels from the impact of external energy (such as the energy of implanted ions and ablation induced stress). This feature provides potential for further realization of waveguide laser or waveguide amplification.

4. Conclusion

In conclusion, ridge waveguides were successfully realized in the Yb$^{3+}$-doped silicate glass using laser ablation assisted proton implantation. The vacancy simulation results indicate that the injected protons are concentrated around 5 $\mu$m below the top surface of the sample, resulting in the decrease of local density and refractive index. In this way, a barrier is formed as a cladding on one side of the waveguide. The morphology of ridge waveguide with two grooves separation of 25 $\mu$m was investigated in detail by optical microscope. The near-field mode measurement shows that only the fundamental mode can be propagated in the ridge waveguide at 976 nm. In the ridge waveguide region, the micro-fluorescence properties are well maintained. This work suggests the ridge waveguide fabricated by femtosecond laser ablation combined with proton implantation in Yb$^{3+}$-doped silicate glass is a promising alternative for integrated active optical device.

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