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The formation and characterization of optical waveguide in Nd:YLF crystal by 4.5-MeV Si ion implantation

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ABSTRACT

The planar waveguides have been fabricated in Nd:YLF crystals by Si implantation. The guiding properties of Si-implanted waveguide are evaluated by the prism-coupling technique and reflectivity calculation method (RCM), exhibiting good confinement and monomode behavior at 632.8 nm. The investigation of the photoluminescence (PL) measurement demonstrates that the luminescence characteristics of the Nd^{3+} ions are not significantly altered by the Si ions irradiation process, whereas the up-conversion (UC) luminescence intensity can be effectively improved. Based on the pump-power-dependent fluorescence, the possible emission mechanism in Nd:YLF is proposed.

1. Introduction

$YLiF_4$ (YLF) crystal is an outstanding laser material in advanced photonics and nonlinear optics owing to its remarkable features such as low effective phonon energy and good chemical stability [1]. Among the various possibilities, rare-earth-doped YLF have been widely studied as promising materials for a broad range of laser operation, acousto-optic device and laser amplifiers [2–6]. So far, the trivalent Nd^{3+} ion has attracted significant attentions because of its unique orbital structures including 17 spectroscopic terms and 41 energy levels which can offer multiple channels for fluorescence emissions. Moreover, the trivalent Nd^{3+}-doped host matrices have received increasing interests as active media to obtain near-infrared (NIR) lasers operating around 1064 nm [6]. Especially, Nd:YLF crystal is much attractive in integrated optoelectronic devices and diode-pumped lasers thanks to its natural combination of the unique laser performances of Nd^{3+} and excellent nonlinear optical properties of YLF crystal [7–9]. In many respects, the miniaturization of lasers into monolithic devices is necessary since the integrated photonic circuits are often conceived as planar surface structure with components that have linear dimensions of micron size. For those potential applications, the design and fabrication of miniaturized waveguide is especially important to obtain high photon density and optical conversion efficiencies. Research on optical waveguides is developing continuously in view of the increasing demand of compact devices. Up to now, various techniques have been developed to fabricate optical waveguides including femtosecond laser writing, ion irradiation, metal diffusion and ion exchange [10–13]. Among those, ion irradiation also ion implantation, as a powerful technique for materials modification, has been demonstrated to be an effective and competitive way to produce high-quality waveguides in more than 100 optical materials for its features of controllability and reproducibility [14]. Additionally, it has been proved that ion irradiation is also useful for modulating the optical and spectral properties of laser materials. So far, optical waveguides using energetic light ions (H, He) or swift heavy ions (C, O, Si) have been extensively investigated [15–20]. Compared with light-ion implantation, low-dose heavy ions implantation can induce large refractive index variations in the implanted region. In 2007, Tan et al. reported their work on the C-implanted Nd:YLF waveguides with fluences of $\sim 10^{15}$ [15]. Recent research reveals that heavy ions Si implantation could form waveguide structures efficiently on the surface of optical materials with much lower doses $\sim 10^{14}$ [18,21]. According to the literature on H— or C—ion-implanted Nd:YLF waveguides, the issues mainly focused on the characterizations of the guiding properties. To our knowledge, the optical waveguides formation in Nd:YLF crystal by Si ions implantation have not been reported. The effect of irradiation on the optical and spectral properties of Nd:YLF has not been fully explored. Moreover, the demand for better performance in high-power application for the different laser concepts in Nd:YLF is ongoing. Thus a clear understanding of the effect of ion irradiation is essential to research on the manipulation of optical and spectral properties of Nd:YLF crystals. Here, in order to explore the possibility of a single-mode planar waveguide formed in the Nd:YLF crystal and to study the photoluminescence features of Nd^{3+} after ion implantation, the 4.5-MeV Si ions irradiation in

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Nd:YLF crystals was carried out at the 1.7 MV tandem accelerator of Peking University. The optical analyses of the waveguide such as refractive index profile and propagation mode distribution as well as fluorescence properties of Nd^{3+} are discussed in detail.

2. Experimental details

A set of z-cut Nd:YLF single crystals (doped with 1.0 at% Nd^{3+}) were implanted by 4.5-MeV Si ions with fluences of 1.0×10^{14} cm^{-2}. All samples were optically polished and cleaned before implantation. During implantation, the samples were titled by 7° from the direction of the ion beam to minimize the channeling effect. The prism-coupling method was used to observe guiding modes of the Nd:YLF planar waveguides with a Model 2010 prism coupler (Metricon 2010, USA) at a wavelength of 632.8 nm with transverse electric (TE) polarization. The accuracy of prism coupler measurements is ± 0.0001. The error is better than 0.001 by uncertainties in the measuring prism angle and index. The reconstruction of refractive index was performed by a program code based on RCM [22]. The electric field distribution of the measured TE mode was obtained to investigate confinement in the implanted waveguides. The UC and NIR emission spectra of the implanted waveguide and the bulk of Nd:YLF crystal were measured on an Edinburgh FS5 spectrometer under excitation with an 808-nm diode laser.

3. Results and discussion

In the past few decades, the prism coupling technique has been well developed to investigate optical properties of many kinds of materials, including dielectric thin films and bulk crystals. It offers the ability to make accurate thickness and refractive index measurements with high resolution. Over the years, it has also been demonstrated to be a powerful technique for optical waveguides characterization. Fig. 1a shows the schematic plot of the prism coupling measurement. In most cases, a laser beam striking the prism is normally totally reflected at the prism base onto a detector. Especially, when the incident angles are at certain discrete values, the light can tunnel across the air gap into the guiding region through the optical propagation mode coupling, resulting in a sharp dip in the intensity of the incident light reaching the detector which is referred to the dark-mode spectrum. Furthermore, the mode numbers, the mode effective refractive indices, as well as the mode types can be determined with respect to the mode plots. Fig. 1b shows the dark-mode spectra of Nd:YLF planar waveguides irradiated

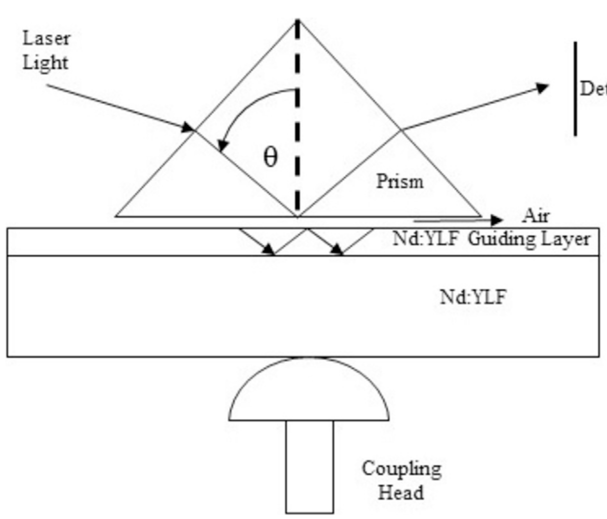

Fig. 1. (a) Schematic of the measurement mechanism of prism coupling method; **(b)** mode plots of the reflected light at a wavelength of 632.8 nm with TE polarization for 4.5-MeV Si-irradiated Nd:YLF.

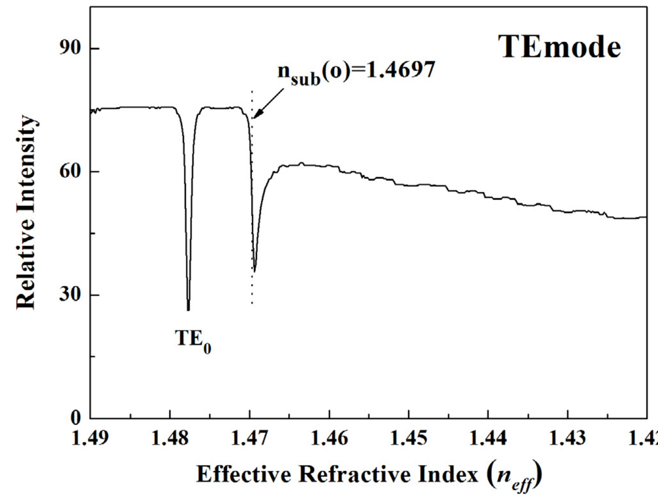

Fig. 1. (*continued*)

by 4.5-MeV-Si ions at fluences of 1.0×10^{14} cm^{-2}, which were recorded by a Model 2010 prism coupler at a wavelength of 632.8 nm. The ordinary refractive index of pristine Nd:YLF crystal (n_{sub} = 1.4697) is also given for comparison. As indicated in Fig. 1b, when the laser beam is employed with TE polarization, one narrow and sharp drop is detected. It should be pointed out that the detectable TE mode is confined by the n_0-enhanced region because of the higher mode effective index comparable with the pristine crystal. According to previous researches, several factors are assumed to be responsible for the refractive index change in implanted crystals, including spontaneous polarization, molar polarization, and molar volume, which could be directly influenced by ion implantation process [21,23,24]. It is well-known that there are two factors dominating the lattice damage in the crystal, the electronic ionizations and the nuclear collisions. In near surface, the electronic interaction induced damage component is responsible for an increase in the refractive index; on the contrary, the other damage component produced by nuclear collision cascade causes lowering of the refractive index [25,26]. Despite these impressive advances, the actual index-raised mechanism of implantation is not completely understood; further research will be carried on.

Since the profile of refractive index is of great importance for characterizing waveguide, different methods have been developed to fit the refractive index profile from the measured experimental modes, such as the inverse Wentzel–Kramers–Brillouin method (WKB) [27], parameterized index profile reconstruction (PIPR) [28], the intensity calculation method (ICM) [29] and RCM. Here, RCM developed by Chandler and Lama was chosen to reconstruct the refractive index profile of Si-ion-implanted Nd:YLF waveguide because it has been proven to be remarkably successful for characterizing the refractive index profiles of ion-implanted waveguide. For the first step, a conceivable profile is assumed, which is characterized by a set of parameters, including the basic shapes of the profile, the indices of the barriers, sample surfaces and substrate, the location of barrier inside the crystals, etc.; then this profile is used to calculate the effective refractive index of each mode by using RCM; finally, adjust certain parameters to alter the refractive index profile until the calculated effective refractive indices match the measured ones with the satisfied error. With these parameters, such a profile is supposed to approximately depict the refractive index behavior in the waveguides. Fig. 2 shows the reconstructed ordinary refractive index profile of Nd:YLF waveguide formed by the 4.5-MeV-Si implantation with fluences of 1.0×10^{14} cm^{-2} based on RCM. As one can see that an enhanced well with a positive index change of ~2.06% is created from the near surface region of the sample, whilst a narrow optical barrier with a lower refractive index is built up at a depth of ~2.4 μm which acts as the