frontiers in Physics

ORIGINAL RESEARCH
published: 23 September 2021
doi: 10.3389/fphy.2021.758071

Enhanced Raman Spectra in Femtosecond Laser Inscribed Yb: YVO_4 Channel Waveguides

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The femtosecond laser writing with double-line technique was employed to fabricate buried channel waveguides with different widths in Yb:YVO_4 crystal. Model profiles of the waveguides were captured using the endface coupling setup at the wavelength of 633 nm under TE and TM polarization. Furthermore, the confocal micro-Raman spectra in bulk and waveguide areas were studied at the wavelength of 633 nm. The enhanced Raman intensity were performed in waveguide areas.

Keywords: Yb:YVO4 crystal, optical waveguide, femtosecond laser inscription, Raman sepectra, optical properties

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Specialty section:
This article was submitted to Optics and Photonics, a section of the journal Frontiers in Physics

Received: *13 August 2021*
Accepted: *13 September 2021*
Published: *23 September 2021*

Citation:
Bao Y-F, Liu T, Kong W-J, Luo H-Q, Liu Y, Liu F-R and Cheng L (2021) Enhanced Raman Spectra in Femtosecond Laser Inscribed Yb: YVO_4 Channel Waveguides. Front. Phys. 9:758071. doi: 10.3389/fphy.2021.758071

INTRODUCTION

Yttrium vanadate (YVO_4) is isostructural and crystallizes in the tetragonal space group D_{4h}^{19} with four molecules per unit cell ($Z = 4$), which is an attractive laser host material for producing new highly efficient micro and diode-pumped systems [1–3]. YVO_4 crystals are largely fabricated at lower cost due to the excellent optical quality with larger hardness and better water insolubility [4–6]. Rare-earth ions doped in YVO_4 exhibit excellent properties [4, 6]. Nd ions doped with YVO_4 in a common diode-pumped solid state laser have been studied extensively [7]. Yb^{3+} ion has a simple two-level electronic band structure. Just like Yb doped laser medium, Yb doped YVO_4 crystals possess strong absorption band near 985 nm, high thermal conductivity, and broad gain bandwidth [8, 9], showing potential applications in continuous-wave, Q-switched and mode-locked [6]. Therefore, the study on the optical properties of Yb:YVO_4 crystals is essential and significant.

As a basics component of integrated photonics, optical waveguide structures can confine light propagation within small volumes. The optical properties perform better in waveguide areas in comparison with the substrate. More than one hundred materials are fabricated as optical guiding structures, including single crystals, polycrystalline ceramics, glasses, semiconductors, and organic materials [10–14]. As a fast, flexible, and cost-effective technique, femtosecond laser inscription has been used to fabricate diverse photonic structures on micro- or nano-scales [13]. Femtosecond laser inscription display controlled properties with ultrashort pulse width, extremely high peak intensity and other adequately inscription parameters [13]. So, channel waveguide structure with double lines in Nd:YVO_4 crystal was studied by femtosecond laser inscription [15]. As an excellent optical materials, waveguides in Nd:YVO_4 crystal have been also fabricated using ion irradiation with proton [16], N [17], Si [18], He [19], O [20] ions and swift Kr ions [21].

The Raman effect was discovered by C.V. Raman in 1928, which can be used to describe the inelastic scattering of photons on a quantized molecular system [22]. As an excellent Raman crystal, the Raman characteristic of YVO_4 is reported by experimental and simulated methods [23]. The

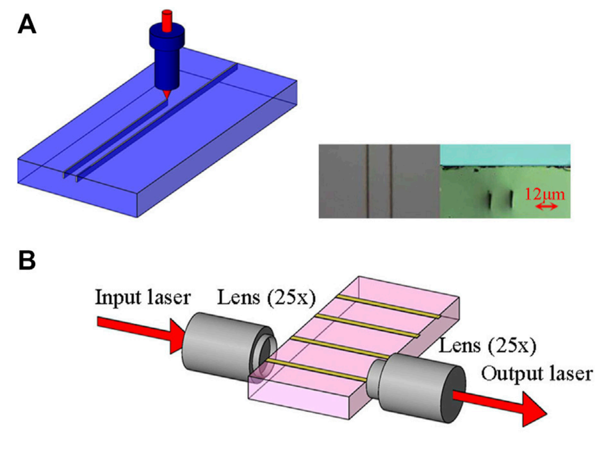

FIGURE 1 | (A) Laser writing setup used in Yb:YVO_4 crystals (left); Schematic photographs of the buried channel waveguide structures in Yb:YVO_4 crystals (right) cross section and top section; **(B)** Endface coupling setup at 633 nm.

TABLE1 | The details of the samples.

Double-line width(μm)	Substrate	6	12	18	24
Writing energy (mW)	0	0.4	0.7	1.1	1.3
Sample	S_0	S_1	S_2	S_3	S_4

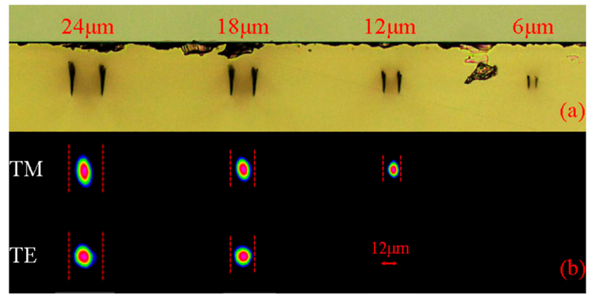

FIGURE2 | (A) Cross-section of the buried channel waveguide structures in Yb:YVO_4 crystals; **(B)** Model profiles of S_2, S_3, and S_4 at 633 nm under TE and TM polarization.

Raman and infrared active modes of YVO_4 crystal were firstly theoretically analyzed and symmetry assigned in Ref. [1]. Nd:YVO_4 crystal has been studied using as self-Raman laser material, based on the Raman peak at ~888 nm in YVO_4 host [17].

Although, Nd:YVO_4 waveguides have been well studied, the waveguide structure of Yb:YVO_4 still need more attentions. Here, channel buried optical waveguides in Yb:YVO_4 crystals were fabricated using femtosecond laser inscription with different widths. Due to the birefringence of uniaxial Yb:YVO_4 crystal, model profiles in the two-line waveguide structures at 633 nm under TE and TM polarization were investigated. The peaks in confocal micro-Raman spectra were recorded and assigned to the Raman modes in the Yb:YVO_4 waveguide areas and substrate.

EXPERIMENTS

The Yb:YVO_4 crystal with dimension 10 (x) × 6 (y) × 4 (z) mm^3, was optically polished and applied to produce waveguides along *y* axis using the double-line technique. A Ti:sapphire amplifier system (Libra, Coherent Inc.) with repetition rate of 1 kHz, maximum pulse energy of 4 mJ, pulse width of 40 fs and central wavelength of 800 nm was used to fabricate the buried channel waveguide structures at the Shanghai Institute of Optics Fine Mechanics, China. A laser beam with a writing speed of 20 μm/s was focused 50 μm below the largest faces in each crystal having a lens with a numerical aperture of 0.55. **Figure 1A** shows the laser writing setup used in Yb:YVO_4 crystals. The details of the samples are shown in **Table 1**, including laser power and width of two - line varies from 6 to 24 μm with a step of 6 μm.

An endface coupling setup was employed to study the near-field intensity profiles of the Yb:YVO_4 crystal waveguides with a He–Ne laser at the wavelength of 633 nm, as shown in **Figure 1B**. Furthermore, we used two microscope objective lens (× 25) to couple the 633 nm laser light through the waveguide structure. The near-field intensity profiles were then recorded using a charge-coupled device camera. A metallographic microscope using reflected polarized light was applied to catch the images of the waveguides at different magnifications. The Raman spectra of the bulk and centers of waveguide areas in the Yb:YVO_4 crystals were recorded with a micro-Raman spectrometer (Horiba/Jobin Yvon HR800) at the wavelength of 633 nm with the laser size of 1 μm at room temperature.

RESULTS AND DISCUSSION

In this study, channel waveguide structures were fabricated by laser writing using the double-line technique in Yb:YVO_4 crystal, as shown in **Table 1**. In order to limit the transmission of light, different writing energies were used in fabricating waveguide structures with different widths. **Figure 2** contains photographs and model profiles of the buried channel waveguide structures in Yb:YVO_4 crystal at the wavelength of 633 nm under TE and TM polarization. The photographs collected using a microscope at cross-section of S_1 (6 μm), S_2 (12 μm), S_3 (18 μm), and S_4 (24 μm) were shown in **Figure 2A**. Many flaws at the junction of the crystal and air originate from optical polishing. Areas between the laser writing two lines can be clearly seen at the endface photographs of S_1, S_2, S_3, and S_4, indicating the possible formation of the waveguide structures with refractive index variation. The model profiles of S_2 (12 μm), S_3 (18 μm), and S_4 (24 μm) that were measured at the wavelength of 633 nm under TE and TM polarization were shown in **Figure 2B**. The dashed lines mean the damage track in S_2 (12 μm), S_3 (18 μm), and S_4 (24 μm). The results show that S_1 cannot confine the 633 nm laser light under both TE and TM polarization, while S_2 only confines the 633 nm laser light under TM polarization. 12 μm (S_2) maybe the lower limit width of mode transmission in Yb:

TABLE 2 | Observed modes of YVO_4 crystals and the corresponding experimental results.

Observed modes (cm^{-1})@633 nm	Experimental modes (cm^{-1})@473 nm[16]	Experimental modes (cm^{-1})@514.5 nm[17]	Experimental modes (cm^{-1})@514.5 nm[8]	Assigned Raman modes [8,16, 17]
153	157	157	157	B_{1g}
258	260	-[17]	260	E_{1g}
375	374	379	379	A_{1g}
485	489	489	490	B_{1g}
813	816	817	816	B_{1g}
836	838	840	839	E_{1g}
888	891	892	891	A_{1g}

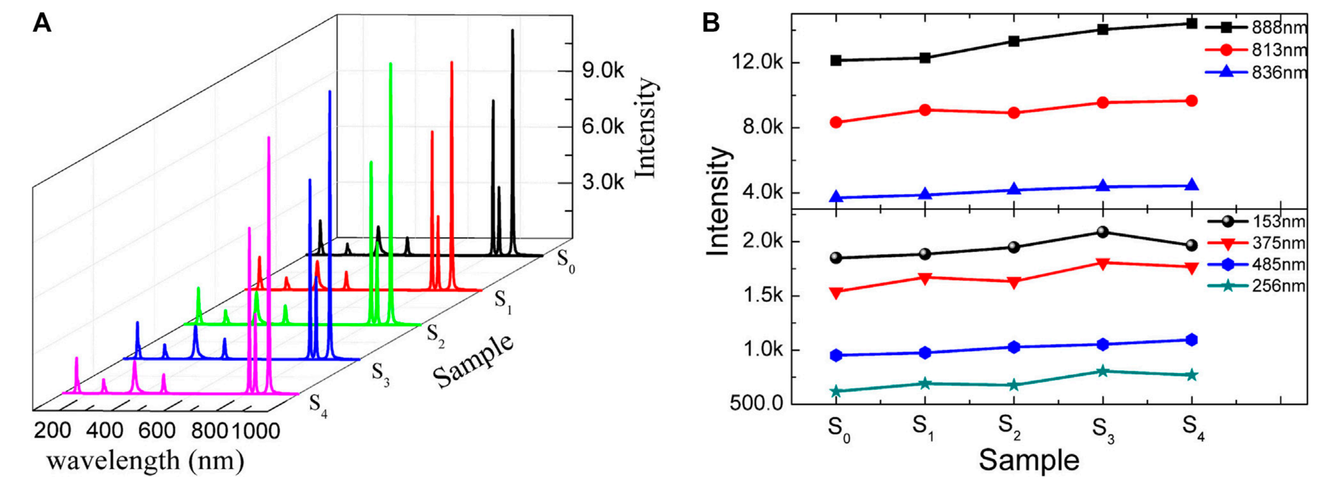

FIGURE 3 | (A) Confocal micro-Raman spectra in Yb:YVO_4 crystal and waveguide areas in S_0, S_1, S_2, S_3, and S_4; **(B)** Intensity of the confocal micro-Raman peaks in Yb:YVO_4 crystal and waveguide areas in S_0, S_1, S_2, S_3, and S_4.

YVO_4 crystals at 633 nm. The results may imply that the width of double lines fabricated by laser writing can influence the light guiding.

To investigate the effect on the laser writing, the confocal micro-Raman spectra in S_0, S_1, S_2, S_3, and S_4 were obtained by using a confocal micro-Raman system with an excitation wavelength of 633 nm at room temperature, as shown in **Figure 3A**, which corresponds to the symmetry species (A_{1g} + B_{1g}) [24]. The spectra were measured vary from 100 to 1,000 cm^{-1} at the smallest end face of the samples. Raman peak positions were listed in **Table 2**, where none extra peak and peak shift existence in waveguide areas and Yb:YVO_4 substrate comparing with the results in Refs. [16, 17, 23]. The experiment modes vary with different wavelengths.

The Raman spectra can provide information about the phonon modes, from the energy of the laser photons shifted by the interaction of the laser light with phonons or other excitations. As reported in Refs. [25, 26], the Raman peaks corresponds to the internal vibrations into VO_4^{3-} group and external vibrations of complex VO_4^{3-} and Y^{3+} ions in YVO_4 unit cell. The symmetric stretch (ν_1), symmetric bending (ν_2), anti-symmetric stretch (ν_3) and anti-symmetric bending (ν_4) of the VO_4 "molecules" are four distinct internal vibrational modes in VO_4 tetrahedron [19, 26, 27]. The peaks at 153, 485, and 813 cm^{-1} are assigned to B_{1g} mode; the peaks at 375 and 888 cm^{-1} are to A_{1g} mode; 258 and 836 cm^{-1} are belongs to the Eg modes [1, 17, 23]. As reported by Zhang et al. [28], the change of peak position in crystal Raman spectrum could disclose the stress and strain in the sample, while the change of full width half maximum (FWHM) indicates crystal quality change. In our work, the peak position and width are both none change, meaning the waveguide areas keep good crystal structures. While one can see that all peak intensities are enhanced in the waveguide areas comparing with the Yb:YVO_4 substrate, as shown in **Figure 3B**. Especially, the enhanced intensity of confocal micro-Raman peaks at 888, 836, and 485 cm^{-1} were performed with increasing waveguide width in S_1, S_2, S_3, and S_4, making the obtained waveguides promising candidates for the development of integrated self-Raman laser sources.

CONCLUSION

We fabricated buried channel waveguides in Yb:YVO_4 crystal using the femtosecond laser writing with double-line technique. The photographs of waveguides structures with the widths of 6, 12, 18, and 24 μm were captured using a metallographic microscope with reflected polarized light. Model profiles at TE and TM polarization were captured using the endface coupling setup at the wavelength of 633 nm. The results imply that the width of two lines fabricated using the laser writing influences the light guiding. The confocal micro-Raman spectra of the bulk and waveguide areas in the Yb:YVO_4 crystal were studied at 633 nm. The enhanced Raman intensity at 888, 836, and 485 cm^{-1} were performed with increasing waveguide width in waveguide areas.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

TL and WK proposed research ideas and plans, TL and YB performed the experiments and measurements and was responsible for writing the manuscript. HL,YL, FL and LC were responsible for experiments and measurements. All authors contributed to the article and approved the submitted version.

FUNDING

This work is supported by National Science Foundation of China (Grant No. No.11805108 and 11805142).

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