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Continuous wave channel waveguide lasers in Nd:LuVO₄ fabricated by direct femtosecond laser writing

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Abstract: Buried channel waveguides in Nd:LuVO₄ were fabricated by femtosecond laser writing with the double-line technique. The photoluminescence properties of the bulk materials were found to be well preserved within the waveguide core region. Continuous-wave laser oscillation at 1066.4 nm was observed from the waveguide under ~809 nm optical excitation, with the absorbed pump power at threshold and laser slope efficiency of 98 mW and 14%, respectively.

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1. Introduction

Neodymium doped vanadate crystals, including yttrium vanadate (Nd:YVO₄), gadolinium vanadate (Nd:GdVO₄), and lutetium vanadate (Nd:LuVO₄), etc., are considered as favorite gain media for solid state lasers owing to their large emission cross-section, high absorption and high thermal conductivity [1–8]. For example, Nd:YVO₄ has become the mostly widely used working medium for the green laser pointers in the hybrid "Nd:YVO₄ + KTiOPO₄" intracavity self frequency doubling system. Among the vanadate family, Nd:LuVO₄ is a new member, which was successfully grown, for the first time, by Maunier *et al.* in 2002 [5]. The absorption cross section σ_{abs} at 808 nm for Nd:LuVO₄ (0.04 at. %), Nd:YVO₄ (0.4 at. %) and Nd:GdVO₄ (1.2 at. %) are reported to be $69 \times 10^{-20} \text{ cm}^2$, $57 \times 10^{-20} \text{ cm}^2$ and $52 \times 10^{-20} \text{ cm}^2$, respectively, whilst the emission cross section σ_{em} at ~1064 nm are determined to be $146 \times 10^{-20} \text{ cm}^2$, $135 \times 10^{-20} \text{ cm}^2$ and $76 \times 10^{-20} \text{ cm}^2$, respectively [5–9], which prove that Nd:LuVO₄ crystals possess

even greater absorption and emission cross sections than those of conventional vanadate crystals. Meanwhile, Nd:LuVO₄ laser operating at 1064 nm [8], 1343 nm [9], 916 nm [10], and 880 nm [11] have been realized.

With respect to bulk geometry, the confinement of light in very small volumes through optical waveguides increases the light intensity to a great extent, resulting in the considerable improvement of some performances in the guiding structures [12, 13]. Waveguide lasers are expected to have relatively low lasing thresholds and comparable efficiencies with respect to their bulk counterparts. In addition, the compact size of the waveguide components offers possibility for further integration of various devices on a single chip to achieve multifunctional photonic applications. Although several techniques, such as oxygen ion implantation [14] and pulsed laser deposition [15], have been utilized to fabricate optical waveguides in Nd:LuVO₄, no laser oscillations were reported based on these waveguides.

Direct femtosecond (fs) laser writing has recently emerged as one of the most efficient techniques for three-dimensional (3D) volume microstructuring of transparent optical materials [16]. By focusing the fs laser pulses on selected positions inside the substrates, permanent refractive index changes, either in the irradiated region or in the surrounding area of modified region, are produced, in such a way that optical waveguides are fabricated. This technique has been proved to be an almost universal technique for waveguide writing in a wide range of transparent materials, including optical crystals [17–22], ceramics [23–26], glasses [27–30], and polymers [31]. By using this method, buried channel waveguides have been produced in Nd:YVO₄ and Nd:GdVO₄ [17–19]. As for Nd doped fs-laser written waveguide lasers, up to now, the highest efficiency (70% slope efficiency) was obtained in Nd:GdVO₄ platform [18], and the maximum output power was 1.3W for Nd:YAG crystalline waveguides [21].

In this work, we focus on the fabrication of buried channel waveguides in Nd:LuVO₄ crystal by using direct fs laser writing and the continuous wave (cw) laser actions in the waveguide.

2. Experiments in details

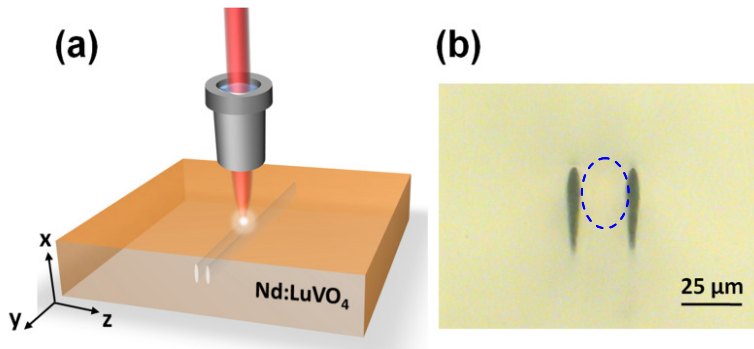


Fig. 1. (a) The experimental set-up for femtosecond laser writing experiments, and (b) the end-face microscope image of Nd:LuVO₄ waveguide sample. The waveguide is located in the open dashed circular region.

The Nd:LuVO₄ (doped by 0.1 at.% Nd³⁺) crystal used in this work was grown by Czochralski method. It was optically polished and cut to dimensions of 2.5(x) × 5.7(y) × 4(z) mm³. The waveguides were produced by using the well-known “double line” technique. An IMRA μJewel mode-locked laser system, delivering pulses with a central wavelength of 1047 nm, pulse duration of 360 fs and repetition rate of 200 kHz, was employed to write waveguides in the crystal. The laser beam, with horizontal polarization, was focused 100 μm below the polished surface by an achromatic lens with a numerical aperture (NA) of 0.6. The sample, fixed onto an Aerotech 3D translation stage, was translated perpendicularly to the laser beam and parallel to the crystallographic y axis (see Fig. 1(a)) with a speed of 1 mm/s and 10 mm/s, respectively. Figure 1(a) shows the schematic diagram of the waveguide fabrication

experimental setup. During the writing process, pairs of parallel tracks with separation distance of 25 μm were formed, one of which is shown in Fig. 1(a). The waveguide was therefore formed in the region between the two tracks due to the stress-induced refractive index changes. For the guiding properties and laser experiments discussed in this paper a waveguide was used, which was fabricated with an average power of 274 mW (corresponding to pulse energy of 1.4 μJ) and a sample translation speed of 10 mm/s. The cross-sections of the tracks are shown in Fig. 1(b).

An end-face coupling arrangement was utilized to investigate the near-field modal profiles of the waveguide with a He-Ne laser at wavelength of 632.8 nm.

The confocal micro-photoluminescence ($\mu\text{-PL}$) properties were obtained by using an argon laser providing 10 mW cw radiations at 488 nm. An Olympus BX-41 fiber-coupled confocal microscope and an XY motorized stage with a spatial resolution of 100 nm were employed. The laser beam was focused into the sample by an oil immersion 100 \times microscope objective with NA = 0.8, exciting the transition of Nd^{3+} ions through from the ground state $^4\text{I}_{9/2}$ up to the $^2\text{G}_{3/2}$ excited state. Then the Nd^{3+} fluorescence emission spectra corresponding to the $^4\text{F}_{3/2}$ to $^4\text{I}_{9/2}$ emission band was back-collected by the same microscope objective and analyzed on a high resolution spectrometer (SPEX500M). Three dimensional spectral maps including the emitted intensity, emission bandwidth, and energy position of the main fluorescence line were obtained by fitting the collected spectra and plotting the obtained values with the aid of software LabSpec $\text{\textcircled{C}}$ and WSMP $\text{\textcircled{C}}$.

The waveguide laser experiment was performed by using a typical end-face coupling system. A cw Ti:sapphire laser (Coherent MBR 110) generating a linearly polarized beam at ~ 809 nm was employed as a pump source. A convex lens with a focal length of 25 mm was used to focus the pump light beam into the waveguide. The generated laser beam from the output facet was collected by a 20 \times microscope objective. The laser oscillation was realized without any cavity mirrors (i.e., the laser cavity was formed directly by two polished facets of the sample). The transmittance of the crystal's faces can be estimated from the refractive index of Nd:LuVO_4 to be close to 90%. After being separated from the residual pump through a dichroic mirror with high reflection at around 808 nm and high transmission at about 1064 nm, the laser emission from the waveguide was detected by the spectrometer, CCD camera or powermeter.

3. Results and discussion

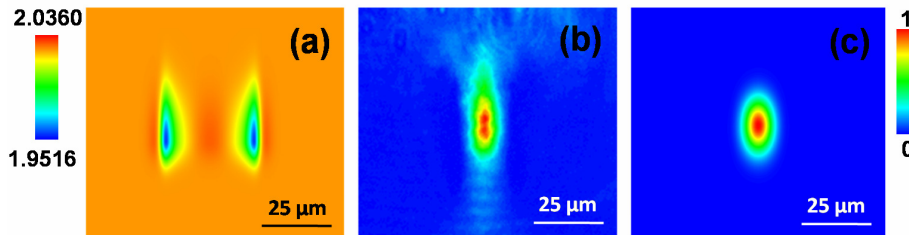


Fig. 2. (a) Reconstructed 2D refractive index profile of the Nd:LuVO_4 waveguide on the cross section, (b) measured near-field intensity of the light of TM_{00} mode, (c) calculated modal profile distribution of TM_{00} mode.

We constructed the 2D refractive index profile of the femtosecond laser written Nd:LuVO_4 waveguide showed in Fig. 1(b) with the method introduced in previous works (see Ref [32]). The reconstructed index profile of waveguides at the cross section is depicted in Fig. 2(a). With these index profiles, we simulated the light propagation in the waveguide by using a commercial software BeamPROP $\text{\textcircled{C}}$ based on the finite difference beam propagation method (FD-BPM) [33]. Figure 2(c) shows the calculated modal profiles of fundamental TM mode (TM_{00}). As can be seen, the combination of refractive index reduction within the tracks ($\Delta n \approx -0.08$) and stress induced positive refractive index change ($\Delta n \approx +0.004$) results in an index distribution, which supports guiding and excellent confinement of the fundamental mode

at a wavelength 633 nm. Meanwhile, the image of the near field light intensity distributions of TM mode from the out facets of the samples, which are captured by a CCD camera, is shown in Fig. 2(b). The waveguide mainly shows a clear single mode character, which is an outstanding feature of relevance in many practical applications. By comparing Fig. 2(c) with 2(b), one can conclude that there is a reasonable agreement between the calculated and experimental data. The propagation loss of the waveguide was estimated to be ~ 2 dB/cm.

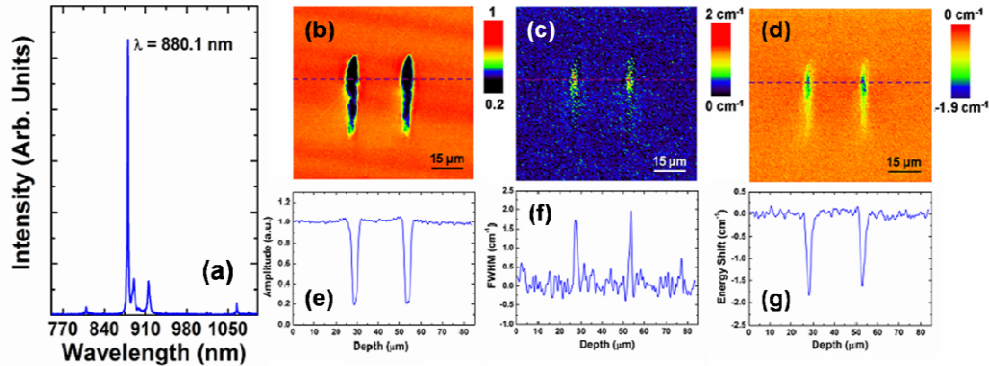


Fig. 3. (a) The room temperature μ -PL emission spectra correlated to Nd^{3+} ions at ${}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{9/2}$ transition of the Nd:LuVO₄ crystal; the 2D mappings of the (b) spatial dependence of the emitted intensity, (c) FWHM and (d) energy shift of the corresponding emission line of Nd^{3+} around 880 nm obtained from the channel waveguide; the 1D distribution of the (e) emitted intensity, (f) FWHM and (g) energy shift of the 880-nm line from the waveguide (corresponding to the regions indicated by dashed lines in the 2D mappings of (b), (c) and (d), respectively).

Figure 3(a) depicts a typical μ -PL emission spectrum corresponding to the ${}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{9/2}$ transition of the Nd^{3+} ions in Nd:LuVO₄ crystal, which consists of a narrow and intense peak at 880.1 nm. In order to obtain the detailed modification of fluorescence properties, we focused on the 880.1 nm emission line and investigated the spatial distribution of the integrated intensity, full width at half maximum (FWHM) of the photoluminescence line and spectral shift in a wide area covering the modified and unmodified Nd:LuVO₄ volumes. The results are displayed in Figs. 3(b), 3(c) and 3(d), respectively. Meanwhile, for easy visualization and comparison, Figs. 3(e), 3(f) and 3(g) depict the 1-D profiles corresponding to the position indicated by the dashed lines in Figs. 3(b), 3(c) and 3(d), respectively. As shown in Figs. 3(a) and 3(d), there is an obvious reduction in the luminescence intensity generated from the filaments volume, which can be attributed to the high density of lattice defects and imperfections in these areas. Similarly, a broadening of the luminescence line also reveals the presence of lattice defects and disorder in the filament area, which can be seen from Figs. 3(b) and 3(e). In addition, the emission line shifts to lower energies at the filament locations, see Figs. 3(c) and 3(f), which correspond to red shifts. It has been proved that red shifts of the μ -PL emission spectra are spatially coinciding with the lateral zones of filaments, and is aroused by the compressive stress [17, 18, 24]. At the same time, from Figs. 3(a)-3(g), similar Nd^{3+} luminescence intensity, FWHM and peak position are observed in the waveguide volumes (between the two filaments) and the bulk of Nd:LuVO₄ crystal, which, in general, means that the spectroscopic properties of the Nd^{3+} ions are well preserved in the waveguide so that the fabricated waveguide emerge as promising integrated laser element.

Figure 4(a) depicts the room temperature waveguide laser power, generated from the Nd:LuVO₄ waveguide, as a function of the absorbed pump power. The experimental data and the linear fit are displayed by solid balls and green solid line, respectively. The laser is found to be stable. It can be determined that the absorbed pump power at threshold (P_{th}) is about 98 mW, whilst the slope coefficient (Φ) is:14%. The maximum laser power achieved is:31 mW for the maximum absorbed pump power of:318 mW, leading to an optical conversion efficiency

of:10%. Figure 4(b) shows the room temperature laser emission spectrum centered at 1066.4 nm when the absorbed power is above the lasing threshold. The inset of Fig. 4(b) illustrates the near-field emission intensity profile of the output laser of TM mode. The laser performance of the waveguide fabricated in this work is comparable to that obtained in previous works reported in [19] and [20] in term of slope efficiency. Nevertheless, when compared with the prior works [17, 18, 21, 25], the performance is relatively low, which might due to the lower concentration of Nd^{3+} (0.1 at.%) in Nd:LuVO_4 crystal and higher propagation loss of the waveguide. Thus, further improvement of the laser performance is expected by increasing the Nd^{3+} concentration or optimizing the writing conditions, i.e., the pulse duration, the writing velocity, or by writing more complex structures.

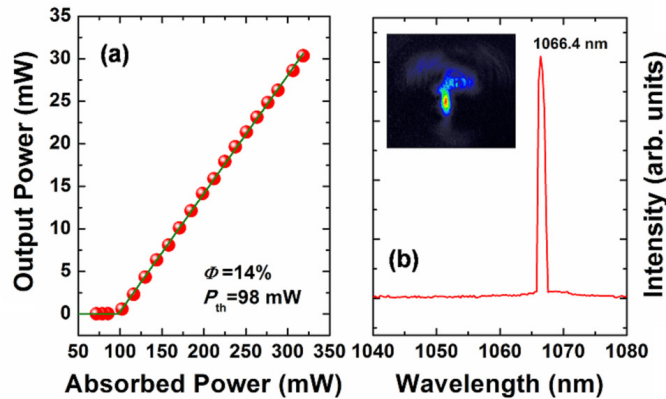


Fig. 4. (a) The cw waveguide laser output power as a function of the absorbed pump power. (b) Laser emission spectrum of the output light at $\sim 1066.4 \text{ nm}$. The inset shows the normalized spatial intensity distribution of the output laser mode

4. Summary

We have reported the fabrication of buried channel waveguides in Nd:LuVO_4 by using femtosecond laser writing. Stable laser operation at 1066.4 nm has been realized with the lasing threshold power of 98 mW and the slope efficiency of 14%. The good laser performance suggests potential applications on construction of integrated laser devices in Nd:LuVO_4 .

Acknowledgments

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