Efficient continuous-wave laser operation at 1064 nm in Nd:YVO_4 cladding waveguides produced by femtosecond laser inscription

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Abstract: Cladding waveguides have been produced in Nd:YVO_4 crystals by using femtosecond laser inscription. Such structures are fabricated with circular cross sections and diameters of ~100-120 μm, supporting multi-mode guidance in the two orthogonal polarizations. At room temperature continuous wave laser oscillations at wavelength of ~1064 nm have been realized through the optical pump at 808 nm with slope efficiency as high as 65% and a maximum output power of 335 mW.

OCIS codes: (230.7370) Waveguides; (140.3390) Laser materials processing; (130.3120) Integrated optics devices.

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1. Introduction

As one of the most excellent gain media for solid state lasers, the neodymium-doped yttrium orthovanadate (Nd:YVO_4) has attracted much attention owing to its outstanding features (e.g., high emission cross section, broad absorption bands, good mechanical and thermal properties) [1]. Optical waveguides can confine light propagation in small volumes, in which higher optical intensities could be reached in respect to the bulks [2]. Benefiting from high intracavity intensity owing to the reduced active volumes, waveguide lasers show many advantages when compared to their bulk counterparts, such as lower threshold and higher laser slope efficiencies [3–6]. In addition, the waveguide laser components are basic minor light sources that can be integrated in single photonic circuit for diverse applications [2]. As of yet, highly efficient waveguide lasers have been realized in a wide range of materials [7–13].

The combination of excellent lasing features of Nd:YVO_4 crystal and the compact configuration of optical waveguides may be promising solution for fabrication of low-cost, highly efficient integrated light sources. Ion implantation was firstly applied to achieve waveguides in Nd:YVO_4, and later the planar waveguide laser was realized in C ion implanted chip (with a slope efficiency of 29.6% and maximum output of 9 mW) [14]. Since 1996, the femtosecond (fs) laser inscription has emerged to be a powerful technique to fabricate waveguides for its unique ability on the three-dimensional (3D) micromachining of many transparent materials [15–17]. Waveguides in Nd:YVO_4 crystal have been already produced by fs laser writing through the "double line" technique [18] and continuous-wave (cw) waveguide lasers were obtained at 1.06 μm with much higher efficiency than those from the ion beam produced Nd:YVO_4 waveguide systems [19,20]. In such a configuration, two parallel laser-damage tracks (usually with negative refractive index change) with separation of 10-20 μm are formed at a certain depth of the crystal, and in the region between the two tracks

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an increase in the refractive index is induced due to the stress-field effect. In fact, the stress-induced waveguides have been realized in a number of crystals, e.g., $LiNbO_3$ [21], Nd:YAG [12,22], Nd:GGG [23], and Nd doped vanadates [13,18–20,23]. For vanadates, e.g., Nd:YVO_4 [24], Nd:$GdVO_4$ [13] and Nd:$LuVO_4$ [23], the fs-laser written stress-induced waveguides exhibited excellent guiding properties as well as lasing performance. Nevertheless, the fs-lasers could be utilized to inscribe an alternative guiding structure, i.e., the cladding waveguides, which was firstly proposed by Okhrimchuk *et al* [25]. In this configuration, the waveguide core is surrounded by a number of fs-laser inscribed tracks with the refractive index lower than the unmodified material, and these tracks could be combined to produce any desired boundaries. Normally such structures are designed with large cross sections compared to the stress-induced waveguides that are limited to 10-20 µm. One of the most intriguing advantages of cladding waveguides is that the cross section could be designed with circular geometry and its diameter could match that of the multimode fibers (fiber-like cross section), which is very promising for the construction of fiber-waveguide-fiber integrated photonic chips. In addition, the larger diameters of cladding waveguides may result in more pump light power coupled into the guided region, and hence bring out the increment of the maximum output powers of the waveguide lasers. Up to now, such cladding structures with circular/elliptic cross sections have been fabricated in a few cubic laser crystals, such as Nd:YAG crystal [8,26] and Cr:YAG crystal [27]. Very recently, we have fabricated the fs-laser inscribed nonlinear cladding waveguides in BiB_3O_6 [28] and $KTiOPO_4$ [29] crystals, which have exhibited superior performances for birefringent second harmonic generations.

In this work, we report on the fabrication of cladding waveguides with fiber-like cross sections in Nd:YVO_4 crystal by fs-laser inscription. Under optical pump of 808 nm light, efficient cw waveguide lasers at 1064 nm have been achieved at room temperature.

2. Experiments in details

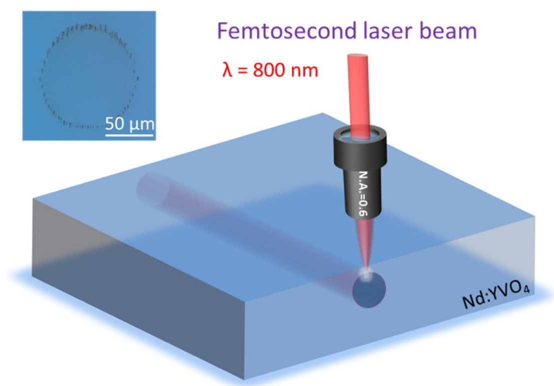

Fig. 1. The schematic of fabrication of Nd:YVO_4 cladding waveguide by fs-laser inscription. The inset shows the microscope image of the cross section of the cladding waveguide with a diameter of 120 µm.

The Nd:YVO_4 crystal (doped by 2 at. % Nd^{3+} ions) was cut with the size of 6 (*a*) × 4 (*a*) × 2 (*c*) mm^3 and optically polished. The cladding waveguides with circular boundaries were produced by using the laser facility of the Universidad de Salamanca (Spain). Figure 1 illustrates schematically the fabrication procedure for the Nd:YVO_4 cladding waveguides. The inset of Fig. 1 shows the microscope image of the end face of one of the cladding waveguides, which clearly exhibits the circular shape surrounded by the fs-laser induced tracks. The waveguide cavity length of these two cladding waveguides was 4 mm. An amplified Ti:Sapphire laser system (Spitfire, Spectra Physics) generating linearly-polarized 120 fs pulses at wavelength of 800 nm with a repetition rate of 1 kHz and a maximum pulse energy of 1 mJ was used for the inscription of the waveguides. The laser beam was focused with a 40 × microscope objective (N.A. = 0.65) through one of the sample surfaces (dimensions 6 × 4

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mm^2). The linear focus of the beam was first placed 110 mm beneath the sample surface and the pulsed energy was set to 1 μJ with the help of a calibrated neutral density filter, and a half-wave plate and a linear polarizer. Under these conditions, the irradiation of the sample produced damage tracks in the beam propagation direction. The sample was located at a XYZ computer-controlled motorized stage with a spatial resolution of 0.2 μm. During the irradiation, the crystal was first scanned by the fs laser pulses at a constant velocity of 0.7 mm/s along the 4-mm axis, by which a damage line was produced inside the sample. The procedure was repeated at different depths and positions of the sample following the desired circular geometry, with a lateral separation of ~3 μm between adjacent scans, from the bottom to the top of the structure (see Fig. 1). As result, two tubular structures containing a chain of parallel tracks were inscribed in the Nd:YVO_4 crystal by the fs-laser. The diameters of the two cladding waveguides at their cross sections were ~100 μm and ~120 μm, respectively. The careful choice of the irradiation parameters (scanning velocity and pulse energy) avoided the formation of cracks inside the crystal and allowed the generation of very clean cladding waveguides.

We measured the modal profiles of the cladding waveguides by an end-face coupling system at 1064 nm and imaged by using an infrared CCD camera. The propagation losses for the cladding waveguides were measured to be ~2.0 dB/cm and ~1.8 dB/cm by using the back-reflection method [30] at 632.8 nm for the 100 μm and ~120 μm waveguides, respectively.

The cw waveguide laser operation experiment was performed by using the end pumping system (similar to that used in [13]) at room temperature. A polarized light pump beam at a wavelength of 808 nm was generated from a tunable cw Ti:Sapphire laser (Coherent MBR 110). A spherical convex lens with focal length of 25 mm was used to couple the pump laser beam into the waveguide. The generated waveguide laser at 1064 nm was collected with a 20 × microscope objective lens (N.A. = 0.4) and imaged by using an infrared CCD camera. A dichroic beamsplitter was used to separate the residual non-absorbed 808 nm pump radiation. We used a spectrometer with resolution of 0.2 nm to analyze the emission spectra of the laser beam from the waveguides. In this work, the 1064 nm laser emission in the two waveguides was achieved without additional dielectric mirrors: the two polished end facets formed the Fabry-Perot cavity for laser oscillations, which results in an output coupler of 99% determined by the refractive index of Nd:YVO_4 ($n \approx 2$) through Fresnel reflection for the air-waveguide interface. The coupling losses were estimated to be 3.1 dB and 2.58 dB (corresponding to coupling efficiency of 49% and 55%) for the 808-nm pump beams into the ~100 μm and ~120 μm waveguides, respectively.

3. Results and discussion

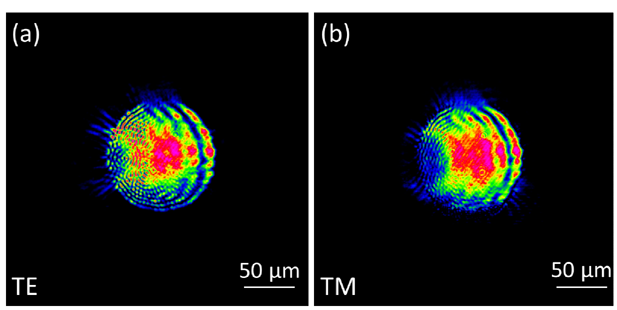

Fig. 2. The spatial modal profiles of the (a) TE and (b) TM modes for the Nd:YVO_4 cladding waveguide of 120 μm diameter at a wavelength of 1064 nm.

Figures 2(a) and 2(b) depict the spatial profiles of the measured TE and TM modes of the Nd:YVO_4 cladding waveguide of 120-μm diameter, respectively. In fact, we found that the waveguide supported guidance in any transverse direction. In addition, the difference of the propagation losses between TE and TM polarized light was only ~5%, showing very good features of the two-dimensional guidance. This could be much advantageous for the waveguide laser when pumping with an unpolarized diode. For the 100 μm diameter cladding waveguide, we obtained similar modal profiles and guiding properties.

The modification of the refractive index in the waveguide region was estimated by measuring the numerical aperture of the waveguide. The maximum refractive index increase (Δn) was calculated to be $\Delta n \approx 4 \times 10^{-3}$ by using the formula

$$\Delta n = \frac{\sin^2 \Theta_m}{2n} \tag{1}$$

where Θ_m is the maximum incident angular deflection at which no transmitted power change occurs, and n = 1.9945 is the refractive index of the unmodified bulk crystal. The obtained Δn value is similar to that reported in [26] for the Nd:YAG crystal cladding waveguides.

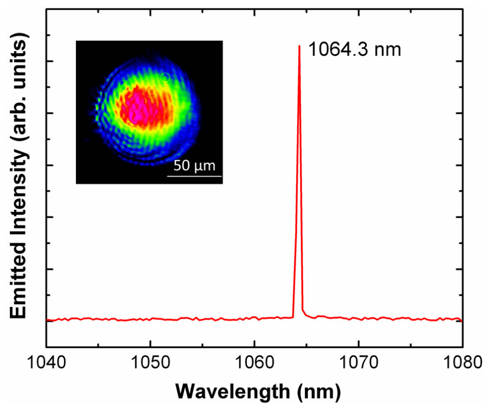

Fig. 3. Laser emission spectra from the fs-laser inscribed Nd:YVO_4 cladding waveguide. The inset depicts the laser modal profiles at lasing wavelength of ~1064.3 nm.

Figure 3 depicts the laser emission spectrum from the fs-laser inscribed Nd:YVO_4 cladding waveguide (120 μm diameter), when the absorbed power is above the lasing threshold. The central wavelength of the laser emission from the cladding waveguide is 1064.3 nm, which corresponds to the main fluorescence of $^4F_{3/2} \rightarrow ^4I_{11/2}$ transition in the Nd^{3+} ions. Similar spectroscopic and modal features for the 100 μm cladding structures have been observed.

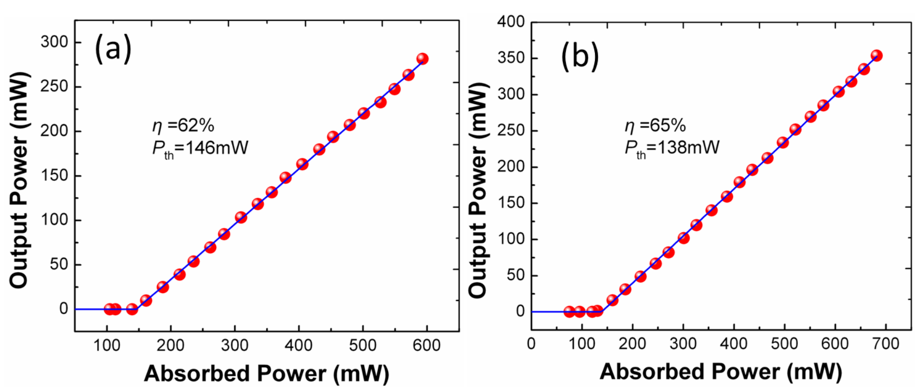

Fig. 4. Output laser powers at 1064.3 nm as a function of the absorbed pump power at 808 nm obtained from the Nd:YVO_4 cladding waveguides with diameter of (a) 100 μm and (b) 120 μm.

Figures 4(a) and 4(b) show the output laser powers (at wavelength of 1064.3 nm) as a function of the 808 nm absorbed powers generated in the Nd:YVO_4 cladding waveguides with diameter of 100 and 120 μm at room temperature, respectively. The absorbed powers were calculated with the reasonable consideration of the coupling efficiency of the pump beam, and the transmittance and reflectivity of the optical elements in the end-pump system [31]. From the linear fit of the experimental data, we have determined that the lasing thresholds are $P_{100,th}$ ≈146 mW and $P_{120,th}$ ≈138 mW for the Nd:YVO_4 cladding waveguides with diameters of 100 and 120 μm, respectively. And the extracted slope efficiencies are η_{100} ≈62% and η_{120} ≈65%, respectively. As the absorbed pump powers monotonically increase, the output laser powers of these two waveguides climbed to maximums at $P_{100,M}$ ≈263 mW and $P_{120,M}$ ≈335 mW at absorbed pump powers of 571 mW and 656 mW, corresponding to optical-to-optical conversion efficiency of Φ_{100} ≈46% and Φ_{120} ≈51%, respectively. By comparison of the data from Figs. 4(a) and 4(b), one can see that the cladding waveguide with a larger diameter possesses superior performance than the shorter diameter cladding waveguide: smaller lasing threshold, and higher slope efficiency and output laser power. The value of lasing threshold is related to the propagation loss and the effective pump area, i.e., $P_{th} \propto \delta \cdot A_{eff}$, where P_{th} is the lasing threshold, δ is the round-trip cavity loss exponential factor (determined by propagation loss of waveguides), and A_{eff} is the effective pump area (determined by both of the pump beam and waveguide geometry). The cladding waveguide of 120 μm diameter possesses larger effective pump area (1.08 times of the 100μm one) but as well lower propagation loss. As a synergy effect, the lasing threshold for large cladding waveguide is still reasonable. Compared with the ion beam produced Nd:YVO_4 waveguides, the cladding waveguides exhibit much higher slope efficiencies and maximum output waveguide laser powers. Compared with the fs-laser inscribed stress-induced Nd:YVO_4 [19] and other vanadate waveguides [13,23], the cladding waveguides exhibit comparable laser performances on both slope efficiencies and output laser powers. The N.A. and waveguide core diameters of the Nd:YVO_4 cladding waveguides match well those of some commercial optical fibers. Such a fiber-like geometry is advantageous to construct fiber-in-coupled pump systems, which is more promising for the further on-chip integration of photonic devices. Future work will be focused on the optimization of the modal profiles (e.g., by changing the diameters of the structures) and further reduction of the propagation losses.

4. Summary

We have fabricated circular-cross-section cladding waveguides in Nd:YVO_4 crystal by using fs laser inscription. Such structures are with diameter of ~100 and 120 μm, supporting good guidance in both of the two polarizations. The cw waveguide lasers at ~1064 nm were realized under the optical pump at 808 nm, reaching the slope efficiency as high as 65% and the maximum output power of as high as 335 mW. The excellent laser performance and the fiber-like geometry indicate potential applications of the fs-laser written Nd:YVO_4 cladding waveguides as highly efficient integrated laser sources in the integrated photonic systems.

Acknowledgments

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