Simultaneous dual-wavelength lasers at 1064 and 1342 nm in femtosecond-laser-written Nd:YVO$_4$ channel waveguides

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Dual-wavelength waveguide lasing at 1064 and 1342 nm corresponding to the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ and $^4F_{3/2} \rightarrow {}^4I_{13/2}$ Nd transitions has been demonstrated in a femtosecond-laser-inscribed Nd:YVO$_4$ channel waveguide. Under 808 nm optical pumping, the obtained laser thresholds at 1064 and 1342 nm were 180 and 210 mW, respectively. The laser slope efficiencies at 1064 and 1342 nm were found to be 15.6% and 1.7%, respectively. © 2011 Optical Society of America

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1. INTRODUCTION

Simultaneous multiwavelength lasing from a single laser medium has attracted continuous attention owing to many potential applications, such as laser medium treatment, holography, laser spectroscopy, military, laser probing, and analysis of the atmosphere [1–5]. Additionally, combined with nonlinear optical frequency conversion, compact and efficient all-solid lasers in three elemental colors (red, green, and blue) could be designed based on dual-wavelength laser, which has great value in projection displays [6,7]. Rare-earth-ion-doped gain materials offer the possibility of laser actions at various wavelengths owing to multiple energy levels of incorporated active ions. For example, neodymium-doped yttrium orthovanadate (Nd:YVO$_4$) crystal allows multiple transitions departing from the metastable level $^4F_{3/2}$ to the lower-lying-energy Stark sublevels $^4I_{13/2}$, $^4I_{11/2}$, and $^4I_{9/2}$, which leads to potential laser radiations ~1.342, ~1.064, and 0.914 μm, respectively [8,9]. If the differences of the simulated emission cross section, fluorescent lifetime, and fluorescent quantum efficiency could be balanced by a specially designed resonant cavity, the laser can simultaneously be generated at multiple wavelengths [5,10,11]. Nd:YVO$_4$ crystal has been identified as one of the promising materials for dual-wavelength operation owing to its high absorption over a wide pumping wavelength bandwidth and large stimulated-emission cross section at both 1064 and 1342 nm. In addition, the ratio of the stimulated-emission cross sections between $^4F_{3/2} \rightarrow {}^4I_{11/2}$ and $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transitions is much smaller than other gain materials, such as Nd:YAG or Nd:YLiF$_4$, which also shows unique advantages for a continuous dual-wavelength laser operation [8].

Optical waveguides are basic components for photonic applications [12]. Channel waveguides confine light within a small volume at two dimensions, by which much high light intensity could be achieved in the guiding structures. With the high overlap of pump beam and waveguide modes, waveguide lasers have shown multiple unique features compared with the lasing in bulk material, such as low lasing thresholds and higher pumping efficiencies [13–15]. Such active guiding structures could act as promising integrated gain devices for diverse applications. Direct inscription of femtosecond pulses has recently emerged as a powerful technique for channel waveguide fabrication [16–18]. Dual-wavelength laser operation has been reported in Nd:YVO$_4$ crystal (1064 and 1342 nm) [8,10]. However, the waveguide laser operations at these two wavelengths have not been realized. In this paper, we report the simultaneous waveguide laser emissions based on the 1064 nm ($^4F_{3/2} \rightarrow {}^4I_{11/2}$) and 1342 nm ($^4F_{3/2} \rightarrow {}^4I_{13/2}$) transitions in a femtosecond-laser-inscribed Nd:YVO$_4$ channel waveguide.

2. EXPERIMENTAL

The channel waveguides were fabricated by direct femtosecond-laser writing. We used an amplified Ti:sapphire laser system (120 fs, 796 nm, and 1 kHz repetition rate) to inscribe a channel waveguide in Nd:YVO$_4$ crystal (*a* cut, doped by 1 at. % Nd^{3+} ions) along the *b* axis. The femtosecond laser was focused by a microscope objective (N.A. = 0.3). The inscription parameters were 16 μJ/pulse and 50 μm/s of translation speed (as used in [18]). Figure 1 shows the image of the waveguide cross section and the measured near-field intensity distribution of waveguide mode. As we can see from Fig. 1, the waveguide just supports single-mode propagation at wavelength of 808 and 1064 nm, and the shape of the modes are similar for these two profiles.

Figure 2 shows the experiment setup for the dual-wavelength lasing operation. A cw Ti:sapphire laser (Coherent MBR 110) was used as the pump source at 808 nm. The polarization of the pump light was set to be parallel along the *c* axis

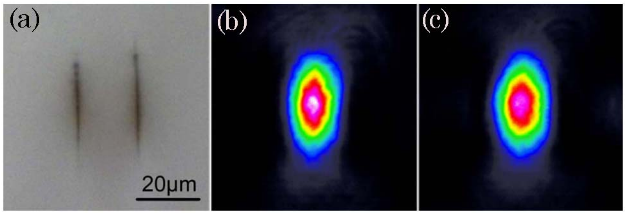

Fig. 1. (Color online) (a) Microscope transmission image of the waveguide cross section; the measured near-field intensity distribution of waveguide mode at (b) 808 and (c) 1064 nm.

of Nd:YVO$_4$. Through a convex lens with a focal length of 25 mm, the pump light was focused onto the input facet of sample and coupled into the waveguide. The coupling efficiency was measured to be ~60%. Mirrors with special designed reflectivity at different wavelengths were adherent to the end facets of the sample as input and output mirrors. Low fluorescence immersion oil ($n \approx 1.52$) was added between the mirrors and the sample in order to increase the transmittance of the sample's facets. The generated light passed through the output coupler and was collected by a 20× microscope objective lens (N.A. = 0.4). A dichroic beam splitter was used to separate the waveguide laser with different wavelengths.

3. RESULTS AND DISCUSSION

The simultaneous multiple wavelength lasing operation needs the satisfaction of oscillation condition for each wavelength. For this purpose, the reflectivity of the input and output mirrors at the corresponding wavelengths should be well designed to approximately balance the threshold. According to oscillation condition of laser, the relationship between threshold and reflectivity of mirrors could be expressed by the following equation [19,20]:

$$P_{\mathrm{th}i} = \frac{hv_i V}{\eta_i \sigma_i \tau_i}\left[\alpha_i + \frac{1}{2L}\ln\left(\frac{1}{R_i r_i}\right)\right], \tag{1}$$

where i (1 or 2) stands for corresponding transition wavelength (1064 or 1342 nm in this work), σ_i is the simulated emission cross section, η_i is the efficiency of the crystal in converting the absorbed optical power to the power of fluorescence, α_i is the loss at the corresponding transition wavelength, R_i and r_i are the reflectivity of input and output mirrors corresponding to transition wavelength, respectively, and V is the volume of the waveguide.

To ensure the simultaneous laser operation at two wavelengths, the threshold in both situations should be similar, which could be modified by the reflectivity of the mirrors at a different wavelength. Here we suppose the threshold is equal to each other, i.e., $P_{\mathrm{th}1} \approx P_{\mathrm{th}2}$, and conduct the relationship of $R_i r_i$ (product of input and output couplers' reflectivity) at corresponding wavelength (1064 or 1342 nm) as follows [19,20]:

$$\ln\left(\frac{1}{R_1 r_1}\right) = 2L\frac{v_2\eta_1\sigma_1\tau_1}{v_1\eta_2\sigma_2\tau_2}\alpha_2 - 2L\alpha_1 + 2L\frac{v_2\eta_1\sigma_1\tau_1}{v_1\eta_2\sigma_2\tau_2}\frac{1}{2L}\ln\left(\frac{1}{R_2 r_2}\right). \tag{2}$$

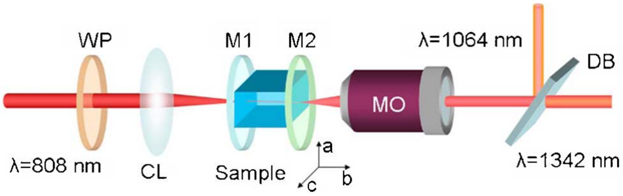

Fig. 2. (Color online) Schematic of the experimental setup for the dual-wavelength waveguide laser operation. WP, wave plate; CL, convex lens; M1, input mirror; M2, output mirror; MO, microscope objective lens; DB, dichroic beam splitter.

As the dual-wavelength laser operates from the same upper laser lever (^{4}F$_{3/2}$), the fluorescence lifetimes of the upper laser level are the same to each other ($\tau_1 = \tau_2$). To calculate the operation condition, the losses and conversion efficiency are supposed to be equal at each operation wavelength. The loss was determined to be ~2 dB/cm, which included the contribution from the low fluorescence immersion oil. The simultaneous emission cross sections are 12×10^{-19} and 6×10^{-19} cm^2 at wavelengths of 1064 and 1342 nm, respectively [21]. Figure 3 shows the correlation between $R_1 r_1$ and $R_2 r_2$ (solid curve) by the calculation mentioned above.

During the experiment, the mirrors were coated with well-designed films. The reflectivity of the input mirror was >99% at 1342 nm and 20% at 1064 nm. And the output mirror has reflectivity of 97% at 1342 nm and 25% at 1064 nm. The products of reflectivity ($R_i r_i$) were marked as a red circle in Fig. 3. As we can see, the point is very close to the calculated line, which suggests the possibility of dual-wavelength waveguide lasing. In addition, the position, which is slightly above the line, indicates slight mismatch of thresholds at different wavelength. According to Eq. (1), the threshold at 1064 nm would be lower than that at 1342 nm.

Figure 4 shows the emission spectra simultaneously happening at around 1064 and 1342 nm with the absorbed pump power above the lasing threshold. As one can see, the FWHM of the emission line is ~0.3 nm at wavelengths of 1064 and 1342 nm, which denotes the dual-wavelength waveguide laser operation.

Figure 5 depicts the output power of waveguide laser at 1064 and 1342 nm as a function of the absorbed pump power at 808 nm. At 1064 nm, the waveguide laser was with pump threshold of 180 mW and with slope efficiency of 15.6%. The

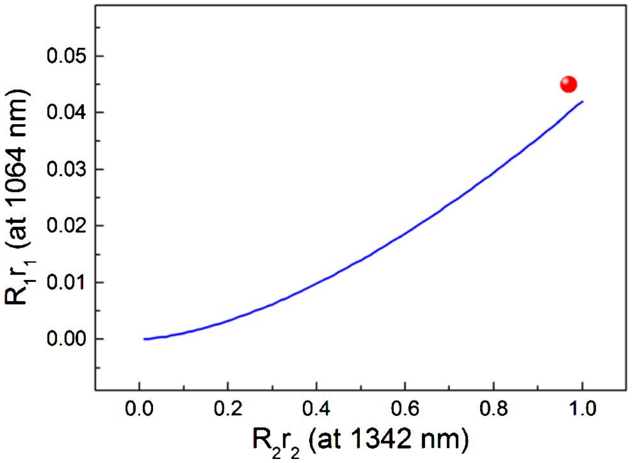

Fig. 3. (Color online) Calculated curve of $R_1 r_1$ as a function of $R_2 r_2$ (solid curve) and experimentally measured value of $R_1 r_1$ and $R_2 r_2$ of mirrors (red circle).

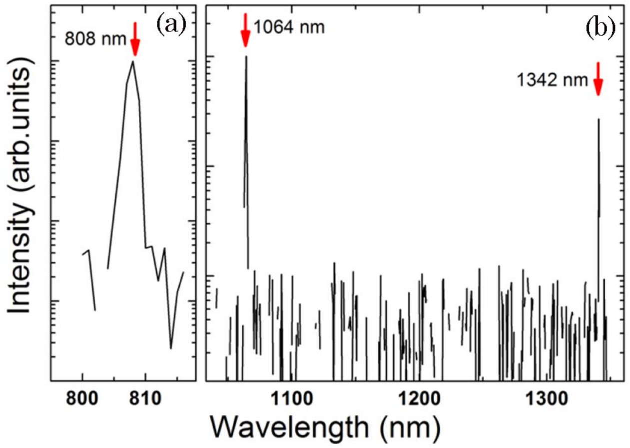

Fig. 4. (Color online) Spectrum of (a) pump and (b) generated laser from the Nd:YVO_4 waveguide.

maximum power of the output light was 49.4 mW with a maximum absorbed pump power of 509 mW, denoting an optical conversion of 9.7%. For the wavelength at 1342 nm, the pump threshold of 808 nm light was 210 mW, and the slope efficiency of laser oscillations was 1.7%. Under optical absorbed pump power of 508.8 mW, the waveguide laser shows the maximum output power was 5 mW at 1342 nm, resulting in optical conversion efficiency of ~1%. At this point it should be noted that the laser performance is very likely limited by the "moderate" propagation losses (close to 2 dB/cm). Therefore, further optimization of the laser performance requires the reduction of this value. In this kind of waveguide (double filament waveguide), the main parameter determining the propagation losses is the spatial overlap between the waveguide mode and the damage tracks (filaments). It has been recently found that, if similar waveguides are inscribed using pulse trains with larger repetition rates (hundreds of kilohertz instead of 1 kHz as we used in this work), the thermal accumulation effects appear, and, as a consequence of this, rapid annealing is activated [22]. This "rapid annealing" induces partial recombination of defects at filaments so that propagation losses are substantially reduced [22]. Therefore, we state that better laser performance could be achieved if similar structures were fabricated by using larger repetition rates.

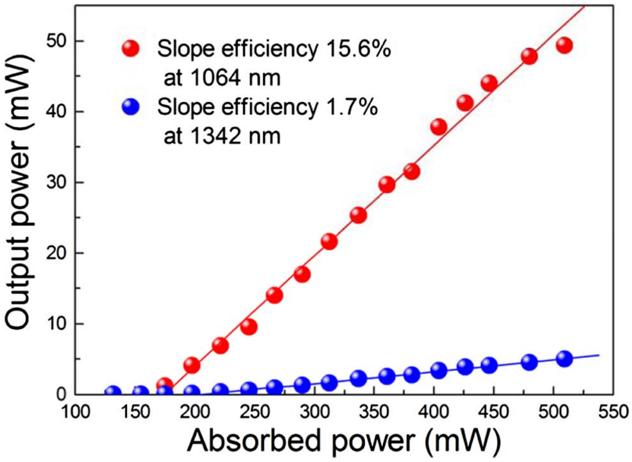

Fig. 5. (Color online) Continuous wave waveguide laser output power at 1064 (red circle) and 1342 nm (blue circle) as a function of the absorbed pump power at 808 nm.

4. CONCLUSION

We report, for the first time to our knowledge, the dual-wavelength waveguide laser operation in a femtosecond-laser-inscribed Nd:YVO_4 crystal at wavelengths of 1064 and 1342 nm. The pump thresholds at 808 nm for the laser oscillations at 1064 and 1342 nm were determined to be 180 and 210 mW, respectively. The slope efficiencies for the dual-wavelength lasers were 15.6% and 1.7%, respectively. The results shown in this work have shown potential applications of Nd:YVO_4 waveguides for dual-laser integrated active devices.

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