Efficient Nd:YVO_4 laser in-band pumped by wavelength-locked 913.9-nm laser diode and Q-switch operation*

Bin Li(李斌)[1,3,†], Peng Lei(雷鹏)[2], Bing Sun(孙冰)[3], and Yang-Bo Bai(白扬博)[1]

[1] *School of Electronics Information Engineering, Tianjin University of Technology, Tianjin* 300384, *China*
[2] *Shenyang Academy of Instrumentation Science Co., Ltd., Shenyang* 110043, *China*
[3] *Tianjin Maiman Laser Technology Co., Ltd., Tianjin* 300111, *China*

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An efficient 1064-nm Nd:YVO_4 laser in-band pumped by a wavelength-locked laser diode (LD) at 913.9 nm was demonstrated. The maximum continuous wave (CW) output power of 23.4 W at 1064 nm was realized with the incident pump power of 40 W, corresponding to a total optical-to-optical efficiency of 58.5%. This is to the best of our knowledge the highest total optical-to-optical efficiency and output power of Nd:YVO_4 laser in-band pumped by a 913.9-nm laser diode. The Q-switched operation of this laser was also investigated. Through a contrast experiment of pumping at 808 nm, the experimental results showed that an Nd:YVO_4 laser in-band pumped by a wavelength-locked LD at 913.9 nm had excellent pulse stability and beam quality for high repetition rate Q-switching operation.

Keywords: in-band pumped, Nd:YVO_4 laser, 1064 nm, Q-switched

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1. Introduction

Reducing thermal effects of lasers and increasing the optical-to-optical efficiency have become two important research points for all-solid-state laser. The quantum defect is the main cause of heat generation and low efficiency. In-band pumping is an excellent way to reduce the quantum defect and increase the optical efficiency of lasers.[1,2] This pumping method pumps the population from the ground state to the upper laser level directly, thus increasing quantum efficiency and decreasing the quantum defect between the pump and the laser photons. During the past few years, numbers of published reports focused on the 88x nm pumped Nd^{3+} lasers,[3–8] however the 88x nm has been discovered to not be the longest wavelength for pumping Nd^{3+} laser. Further reduction of the quantum defect can be achieved by pumping Nd^{3+} ions from the thermally excited high Stark sublevel of the ground state to the upper laser level by using a pump source with longer wavelength. Goldring and Lavi reported an Nd:YAG laser with a Ti:sapphire laser as a pump source at 946 nm in 2008 for the first time. An output power of 60 mW was obtained for a double pass pumping at 946 nm in a 6-cm long 1.1-at.% doped Nd:YAG crystal.[9] In 2009, Sangla *et al.* reported a diode-pumped Nd:YAG laser at 938 nm, but only 6 W of continuous wave (CW) laser emission at 1064 nm was obtained under an absorbed pump power of 28 W at 938 nm.[10] Although the experimental results demonstrated the very low heat generation of in-band pumping at 938 nm, the optical-to-optical efficiency (for incident pump power was only 5%, for absorbed pump power was 21.4%) is not acceptable for practical applications. In the same year, they demonstrated an output power of 11.5 W for Nd:YVO_4 laser pumped by a common 915-nm laser diode with a line-width of 3 nm and the total optical-to-optical efficiency was only 41%.[11] The thermal lens focal length was also measured in their research. The experiment showed that the thermal lens effect of Nd:YVO_4 for an absorbed pump power of 14.6 W at 914 nm was one order of magnitude lower than that measured under hardly 800 mW of absorbed pump power at 808 nm. Although in-band pumping at 914 nm can reduce the thermal effects effectively, the total optical-to-optical efficiency is not high due to the narrow absorption line-width and low absorption coefficient. To overcome these disadvantages, in this paper, we reported an Nd:YVO_4 laser pumped by a wavelength-locked 913.9-nm LD with a line-width of only 0.4 nm. Meanwhile a short fiber was used to maintain the high polarization ratio of the pump source, thereby further increasing the pump absorption. The experimental results showed that the configuration of high polarization ratio 913.9-nm wavelength-locked LD end pumped Nd:YVO_4 could greatly improve the total optical conversion efficiency. A CW output power of 23.4 W at 1064 nm was achieved with respect to the incidence pump power of 40 W, corresponding to the total optical-to-optical efficiency of 58.5% and slope efficiency of 59.1%; for absorbed pump power, the optical-to-optical efficiency and slope efficiency were 71.6% and 72.4% respectively. Finally, the Q-switched operation behavior of laser in-band pumped by a wavelength-locked LD at 913.9 nm was also studied. Through

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†Corresponding author. E-mail: hawkbaby@163.com
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contrast experiment of pumping at 808 nm, the experimental results showed that the wavelength-locked 913.9-nm in-band pumped laser had excellent pulse stability and beam quality for high repetition rate Q-switching operation.

2. Experiment arrangement

The experimental arrangement is shown in Fig. 1. The gain medium was a 1.5-at.% doped with the dimension of 3 mm×3 mm×20 mm Nd:YVO_4 crystal with both end faces AR coated at 914 nm and 1064 nm. The laser crystal was wrapped in indium foil and placed inside a water-cooled copper mount, which was held at 25 °C. The pumping source was a semiconductor laser with a center emission wavelength of 914 nm (25 °C), and a Volume Bragg Grating (VBG) was used to lock its emission wavelength. VBG is fabricated using a holographic technique to create a modulated structure with periodic variation of refractive index on photosensitive glass, frequency-selective reflection can occur if the wavelength of the incoming light meets the Bragg diffraction condition, it is given by $\lambda_B = 2n\Lambda$, where Λ is the grating period, and n is the refractive index of the grating material. The VBG was arranged outside the semiconductor laser chip, an external cavity was formed between the VBG and chip. Therefore, the output wavelength of the laser was locked to the Bragg wavelength by the external cavity. In our experiment, the central emission wavelength of the semiconductor laser locked by VBG was 913.9 nm and the line-width was 0.4 nm. The variance ratio of spectrum with temperature was 0.01 nm/K, which matched well with the absorption peak of Nd:YVO_4 at 914 nm. Its emission spectrum is shown in Fig. 2. The shortcomings of the narrow absorption bandwidth of in-band pump can be overcome by using a wavelength locked laser diode as the pump source. The core diameter of the output fiber was 400 μm with a numerical aperture of 0.22. Finally, the pump source maximum output power was 40 W.

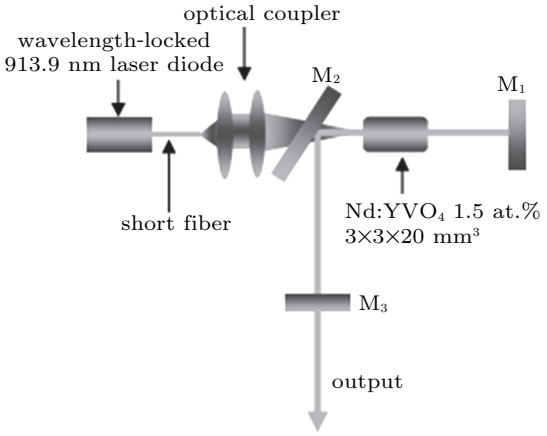


Fig. 1. Experimental setup.

As vanadate crystals present anisotropic properties ($\alpha_a = 0.65\ \mathrm{cm}^{-1}$ and $\alpha_c = 0.46\ \mathrm{cm}^{-1}$ for 1.5-at.% crystal and a common 914-nm laser diode pumping), in order to further increase the absorption of pumping light, a short fiber length of only 90 mm was used in our experiment to maintain the polarized emission characteristics of a laser diode, the pump light had a polarization ratio of ∼ 28 : 1 via fiber coupling. Furthermore, the 913.9-nm pump light was polarized along the c axis of the Nd:YVO_4 crystal (α polarization), the radius of the pump light in the Nd:YVO_4 crystal was 0.25 mm. In order to eliminate the influence of residual pump light on measuring results, the L-cavity structure was adopted to make the laser and pump light travel in a different direction, so that the laser output power could be measured accurately. The plane mirror M_1 had a high reflectivity of 99.8% at a wavelength of 1064 nm. M_2 was a 45° flat dichroic mirror that was coated for high reflection at 1064 nm ($R > 99.8\%$), and high transmission at 914 nm ($T > 96\%$). M_3 was the output mirror with a transmission of 15% at 1064 nm. The whole resonator was ∼ 150 mm in length.

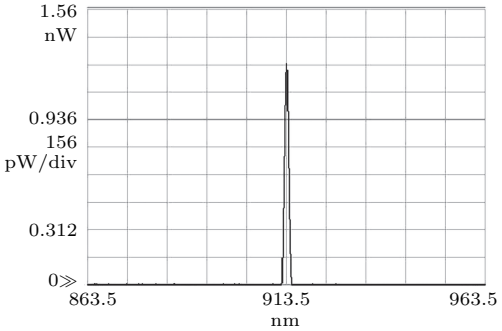


Fig. 2. The emission spectrum of the wave-locked laser diode.

3. Results and discussion

The absorption coefficient of 1.5-at.% doped Nd:YVO_4 crystal at the temperature of 25 °C was 0.85 cm^{-1}, corresponding to 81.7% of the total absorbed power, which was much higher than the previously reported value of 0.58 cm^{-1}.[11] The main reasons for the high absorption were as follows. The first was that the pump source was a wavelength-locked 913.9-nm laser diode with an emission bandwidth of only 0.4 nm, which matched well with the absorption band of Nd:YVO_4 around 914 nm; the other was that the short fiber used in our experiment contributed to the relatively high polarization ratio of the pump light, and the absorption of pump light was further enhanced. Figure 3 shows 1064-nm laser output power versus absorbed pump power and total pump power, with the absorbed pump power of 32.7 W, the output power of 23.4 W was obtained at the incident pump power of 40 W, with the corresponding optical conversion efficiency of 58.5% and slope efficiency of 59.1%. Meanwhile, the optical-to-optical efficiency and slope efficiency relative to absorbed pumping power were 71.6% and 72.4% respectively. Figure 4 shows 1064-nm laser output power versus temperature (15 °C–40 °C) at the same pump power of 32 W with

913.9-nm wavelength locked laser diode and common 915-nm laser diode as pump sources, the experimental results showed that the output power of the laser in-band pumped by the wavelength locked LD at 913.9 nm was not sensitive to temperature fluctuation.

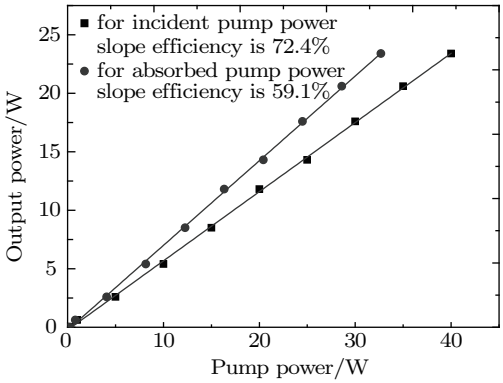


Fig. 3. Output power versus absorbed pump power and total pump power.

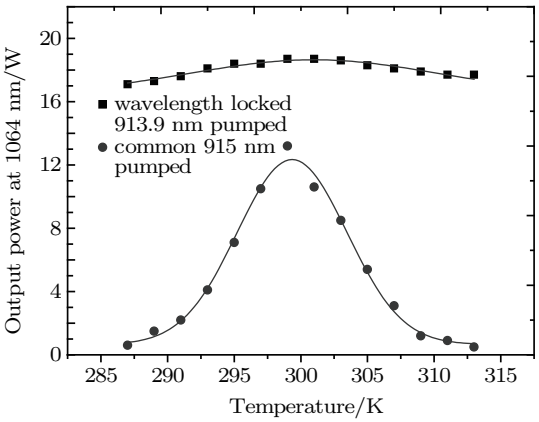


Fig. 4. Output power versus temperature.

We also investigated the Q-switched operation of Nd:YVO_4 laser pumped by wavelength locked LD at 913.9 nm. A contrast experiment with pumping at 808 nm was carried out with the same absorption pump power under the same conditions. A 0.2-at.% doped Nd:YVO_4 with the dimension of 3 mm×3 mm×15 mm was used as a gain medium for pumping at 808 nm. By adjusting the temperature of the 808-nm laser diode heat sink, we obtained the same absorption pump power for pumping at 808 nm and 913.9 nm. An acousto–optic Q-switch was inserted between M2 and M3, while M3 was replaced with a 40% output coupler. Using a wavelength locked 913.9-nm LD as the pump source, a maximum CW output power of 18.1 W was obtained for 27 W of absorbed pump power, while for pumping at 808 nm, a CW output power of 14.4 W was obtained under the same absorption pump power. Figure 5 shows the output power as a function of repetition rate. When the modulation frequency dropped from 150 kHz to 60 kHz, the output power of pumping at 808 nm had a falling rate nearly the same as that of wavelength locked pumping at 913.9 nm. However, as the modulation frequency was less than 60 kHz, the output power of wavelength locked pumping at 913.9 nm decreased faster than 808-nm pumping. Especially the output power of wavelength-locked pumping at 913.9-nm declined dramatically with repetition frequency less than 30 kHz. This phenomenon was mainly attributed to the serious up-conversion at a lower repetition rate for high concentration crystals, since the up-conversion rate can be written as $\gamma\Delta n^2$,[12–16] where γ and Δn are the up-conversion coefficient and the population inversion density respectively. It can be seen that the up-conversion rate increases quadratically with the concentration, especially the high concentration crystals Q-switched operation at the low repetition rate, in which more population inversion can be stored in the gain medium, which leads to an increase in the number of up-conversion and fluorescence quenching.

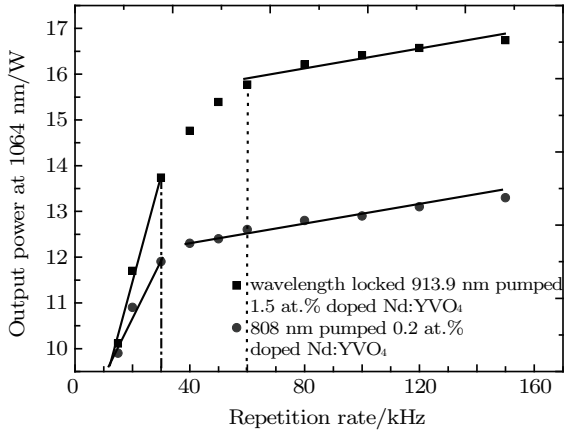


Fig. 5. The output power versus repetition rate under 808 nm and wavelength-locked 913.9-nm pumping.

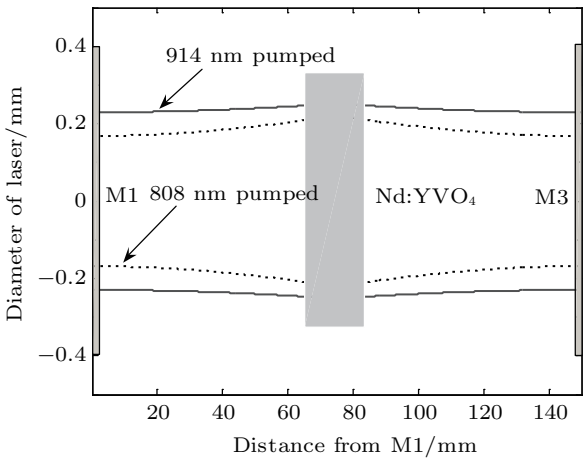


Fig. 6. Beam diameter in the cavity of 808-nm and 914-nm pumping.

The beam quality factors of 808 nm and wavelength-locked 913.9-nm pumping were measured at the same output power of 12.5 W with the repetition rate of 60 kHz. M_x^2 and M_y^2 were 1.23 and 1.26 in two orthogonal directions respectively for wavelength-locked 913.9-nm pumping. M_x^2 and M_y^2 for 808-nm pumping, however, were 2.89 and 2.86 respectively. Figure 6 shows the spot distribution of the oscillating laser

in the cavity pumping at 808 nm and 913.9 nm. Compared with pumping at 808 nm, the oscillating laser beam inside the cavity for 913.9-nm pumping had a larger mode volume and better mode matching with the pumping, so the beam quality factor of wavelength-locked 913.9 nm pumping is better than that of 808-nm pumping. The stability of the Q-switching operation under LD pumping at 808 nm and wavelength-locked 913.9 nm at 60 kHz are shown in Fig. 7, from which we can see that the pulse shape of wavelength-locked 913.9-nm pumping is more stable than that of 808-nm pumping. It is because the multi-mode operation of 808-nm pumping can seriously affect the stability of Q-switching operation, that the gain competition between transverse modes will result in the uncertain building-up time of pulse and the pulse energy jitter, thus in turn, the Q-switching operation under 808-nm pumping is with serious temporal jitter and unstable. The pulse width was 40 ns at 60 kHz of 913.9-nm pumping.

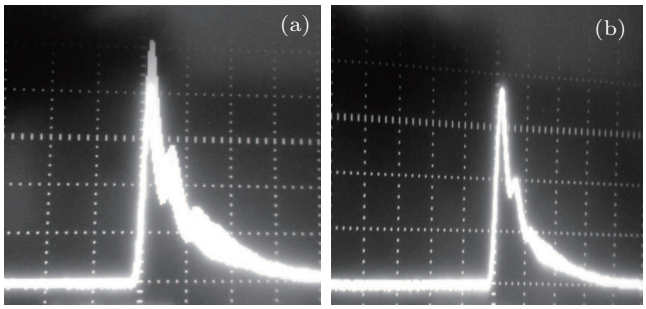


Fig. 7. The stability of the Q-switching operation (a) 808-nm pumping, (b) wavelength-locked 913.9-nm pumping.

4. Conclusion

In conclusion, we have demonstrated a high power and highly efficient 1064-nm Nd:YVO_4 laser in-band pumped by a wavelength-locked laser diode at 913.9 nm. In order to further increase the pumping absorption, a short fiber length of 90 mm was used in the experiment to maintain the polarized emission characteristics of the laser diode. An output power of 23.4 W was achieved with respect to the incidence pump power of 40 W, corresponding to the total optical-to-optical efficiency of 58.5%. This is to the best of our knowledge the highest total optical-to-optical efficiency and output power of Nd:YVO_4 laser with in-band pumping at 914 nm. In addition, compared with the results of 808-nm pumping, the experimental results showed that the wavelength locked 913.9 nm in-band pumped laser had excellent pulse stability and beam quality for high repetition rate Q-switching operation.

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