Continuous wave and passively Q-switched Nd:$Lu_{0.15}$-$Y_{0.85}VO_4$ laser with 885 nm direct pumping*

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The 885 nm direct pumping directly into the $^4F_{3/2}$ emitting level of Nd^{3+} is applied on an Nd:$Lu_{0.15}Y_{0.85}VO_4$ crystal. The maximum output power of 2.8 W for continuous wave (CW) operation is obtained. For Q-switched operation, the maximum average output power is 1.2 W with pulse repetition of 23.69 kHz and pulse width of 35 ns at the pump power of 27.9 W. The high-quality fundamental transverse mode can be observed owing to the reduction of thermal effect for Nd:$Lu_{0.15}Y_{0.85}VO_4$ crystal by 885 nm direct pumping.

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The Nd:$Lu_xY_{1-x}VO_4$ crystal is an isomorphism of Nd:YVO_4 and Nd:$LuVO_4$ crystals[1], which leads to inhomogeneous broadening of the gain spectrum[2]. The mixed crystal Nd:$Lu_xY_{1-x}VO_4$ is a potential candidate for the solid-state laser with broadband, high power and high repetition rate[2]. Some characteristics of continuous wave (CW), Q-switched and mode-locked laser operation for Nd:$Lu_xY_{1-x}VO_4$ crystal have been reported[1-10]. The similarity of all these lasers is that the traditional pump light wavelength of 808 nm is used to pump Nd^{3+} in Nd:$Lu_xY_{1-x}VO_4$ crystal.

Despite above merits of Nd:$Lu_xY_{1-x}VO_4$ crystal, its weakness, in comparison with Nd:YAG crystal, is also obvious owing to the lower thermal conductivity[2], which is less than half of that of Nd:YAG[11], and results in the considerable heat in the crystal to destruct the stability of cavity under 808 nm pump light. The direct pumping scheme at 885 nm for Nd-doped crystals can pump Nd^{3+} from the ground state and the thermally excited ground levels to upper lasing levels and reduce the Stokes shift losses between the pump and lasing photon to improve the quantum efficiency. Consequently, the direct pumping scheme can product less heat in the Nd-doped crystal. It has demonstrated the significant benefit compared with the traditional band excitation pumped at 808 nm in previous works[12-17].

In this paper, the 1 064 nm CW and passively Q-switched Nd:$Lu_{0.15}Y_{0.85}VO_4$ lasers under diode pumping at 885 nm, directly into the $^4F_{3/2}$ emitting level of Nd^{3+}, are demonstrated. The Cr:YAG crystal is used as a saturable absorber. At the pump power of 27.9 W, the maximum output power and the average output power are 2.8 W and 1.2 W for CW and Q-switched operation, respectively. The repetition rate of 23.67 kHz and the pulse width of 35 ns are obtained. The high-quality fundamental transverse mode can be observed because of the reduction of thermal effect for Nd:$Lu_{0.15}Y_{0.85}VO_4$ crystal by 885 nm direct pumping.

The length of Nd:$Lu_{0.15}Y_{0.85}VO_4$ crystal used in our experiment is 10 mm, and the fluorescence spectrum is measured with the excitation wavelength of 885 nm at room temperature (SpectraPro 500i).

The schematic diagram of the 1 064 nm Nd:$Lu_{0.15}Y_{0.85}VO_4$ laser is shown in Fig.1. A simple and compact linear cavity is designed, and its length is about 25 mm. The pump source is a fiber-coupled CW diode laser (JENOPTIK Laser GmbH) emitting at 885 nm. The diameter of the fiber core is 400 μm with the numerical aperture of 0.22. The 885 nm pump light is collimated and focused into the Nd:$Lu_{0.15}Y_{0.85}VO_4$ crystal with diameter of 200 μm by two coupling lenses, which give the coupling efficiency of 90%. M_1 is a plane mirror and coated for high transmission (HT) at 885 nm (T>90%) and high reflection (HR) at 1 064 nm (R>99.9%). In order to reduce the loss of the laser cavity and increase the absorption of the pump light for Nd^{3+}, both sides of the Nd:$Lu_{0.15}Y_{0.85}VO_4$ crystal are HT coated for 1 064 nm (T>99.8%) and 885 nm (T>99%). The output coupler (OC) M_2 is a planoconcave lens with curvature radius of 100 mm, and the transmission at 1 064 nm is 15%. In order to remove the heat generated in the gain medium, the Nd:$Lu_{0.15}Y_{0.85}VO_4$ crystal is wrapped with indium

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foil and mounted in a water cooled copper heat sink, and the water temperature is maintained at 10 °C during the experiment. The CW laser operation is studied firstly, and the pulse laser operation is carried out by inserting a Cr:YAG crystal as saturable absorber into the cavity. The initial transmission of Cr:YAG crystal is 85%, and both sides are coated for HT at 1 064 nm (T>99.8%). The average output power is recorded by a laser power meter behind the OC. The temporal shape of the output laser pulse is recorded by a fast photodiode with a rising time of 350 ps and a digital oscilloscope (Tektronix 3052C, 500-MHz bandwidth and 5.0 GS/s). The transverse mode of the output is recorded by a laser beam analyzer (OPHIR).

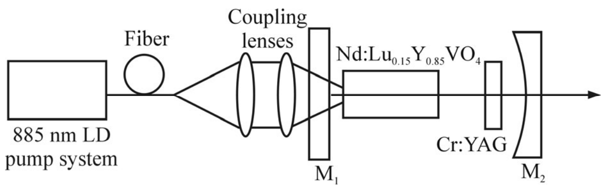
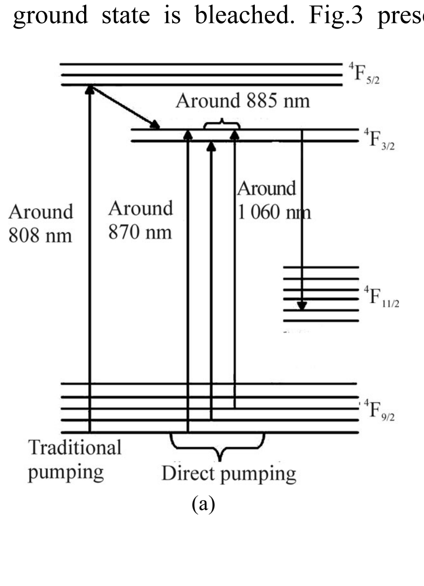
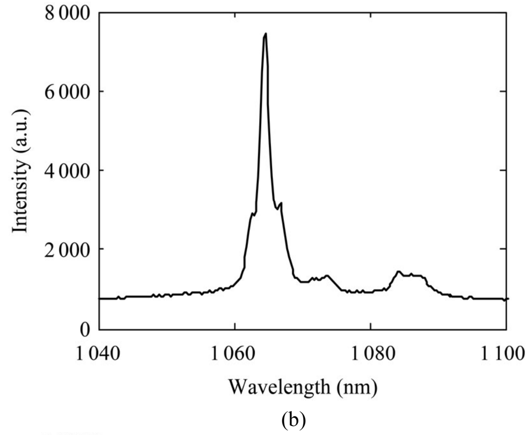


Fig.1 Schematic diagram of the 1 064 nm $Nd:Lu_{0.15}Y_{0.85}VO_4$ laser

The energy level transition diagram of the traditional pumping and the direct pumping from either the ground level or thermally excited Stark components of the ground state to upper lasing level of Nd^{3+} is illustrated in Fig.2(a). Because of the higher quantum efficiency and the absence of relaxation from $^4F_{5/2}$ to $^4F_{3/2}$, the direct pumping method products less heat in the medium, which is advantageous for the stability of cavity. Fig.2(b) shows the fluorescence spectrum of $Nd:Lu_{0.15}Y_{0.85}VO_4$ from 1 040 nm to 1 100 nm with the excitation wavelength of 885 nm, and Fig.2(c) shows the laser emission spectrum of $Nd:Lu_{0.15}Y_{0.85}VO_4$ laser.

For Cr^{4+} in Cr:YAG crystal, its characteristic of saturable absorption plays a key role in the passively Q-switched laser operation[18,19]. The relaxation from the first excited state is in the microsecond region, and it can be used to generate nanosecond order Q-switched pulses when the ground state is bleached. Fig.3 presents the





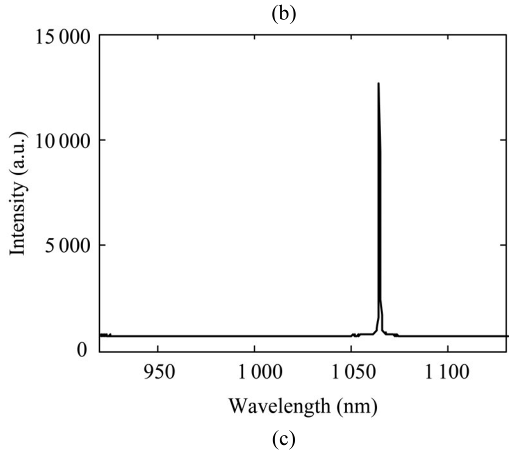


Fig.2 (a) Energy level transition of traditional pumping and direct pumping for Nd^{3+}; (b) Fluorescence spectrum of $Nd:Lu_{0.15}Y_{0.85}VO_4$ from 1 040 nm to 1 100 nm with the excitation wavelength of 885 nm; (c) Laser emission spectrum of $Nd:Lu_{0.15}Y_{0.85}VO_4$ laser

output powers of CW and passively Q-switched $Nd:Lu_{0.15}Y_{0.85}VO_4$ lasers as a function of the incident pump power. The threshold pump powers are about 0.4 W for CW operation and 1.7 W for Q-switched operation, respectively. The obtained maximum CW output power is 2.8 W, and the maximum average output power of Q-switched pulse is 1.2 W at the incident pump power of 27.9 W.

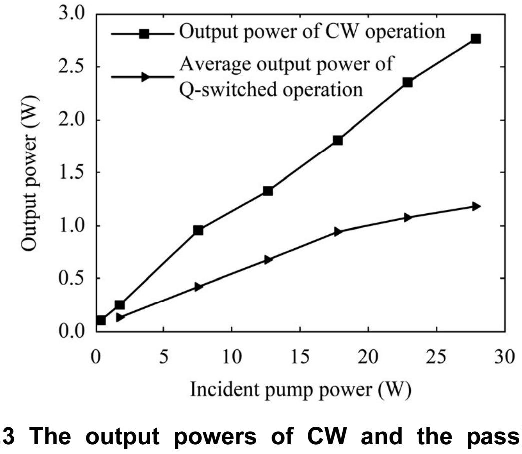


Fig.3 The output powers of CW and the passively Q-switched $Nd:Lu_{0.15}Y_{0.85}VO_4$ lasers as a function of the incident pump power

Fig.4 shows the repetition rate and the pulse width of the 1 064 nm Q-switched pulse as a function of the incident pump power. It is found from Fig.4(a) that the repetition rate of Q-switched pulses increases with the pump laser power, and 23.69 kHz pulse sequence is obtained corresponding to the maximum average output power. The pulse width is from 45 ns to 35 ns with the change of the incident pump power as shown in Fig.4(b).

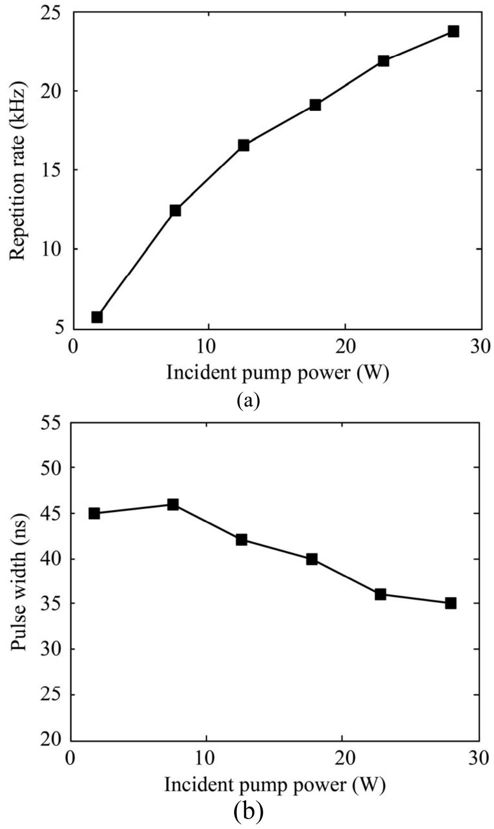
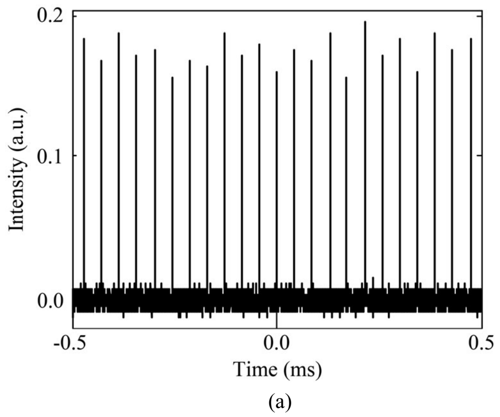


Fig.4 (a) Repetition rate and (b) pulse width of the 1 064 nm Q-switched pulses as a function of incident pump power

The oscilloscope trace of 1 064 nm Q-switched pulses at the pump power of 27.9 W corresponding to the average output power of 1.2 W is shown in Fig.5(a), and the repetition rate is 23.69 kHz. The corresponding temporal behavior is recorded in Fig.5(b) with the pulse width of 35 ns.



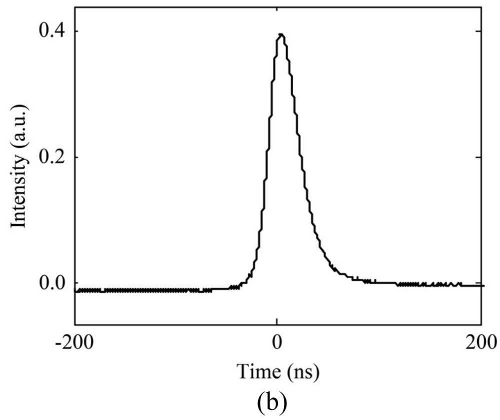


Fig.5 (a) Oscilloscope trace of 1 064 nm Q-switched pulses at pump power of 27.9 W; (b) Pulse shape of the 1 064 nm Q-switched $Nd:Lu_{0.15}Y_{0.85}VO_4$ laser with the pulse width of 35 ns corresponding to (a)

Fig.6 presents the dependence of the average Q-switched pulse energy on the pump power, which is determined by the average output power and repetition rate. The peak power of Q-switched pulse as a function of incident pump power is shown in Fig.7, and it is determined by the pulse energy and pulse width. The pulse energy and peak power are 50 μJ and 1.4 kW, respectively, with the pump power of 27.9 W.

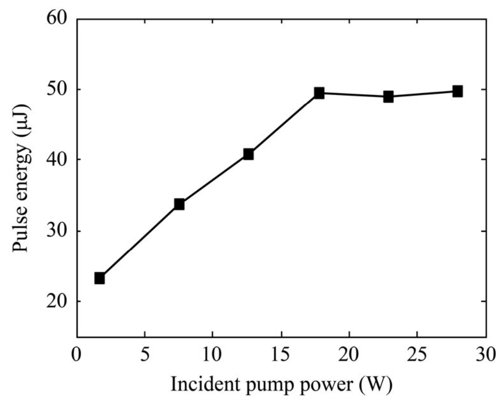


Fig.6 Average Q-switched pulse energy as a function of incident pump power

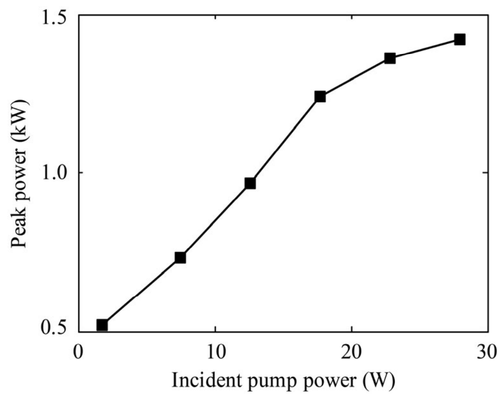
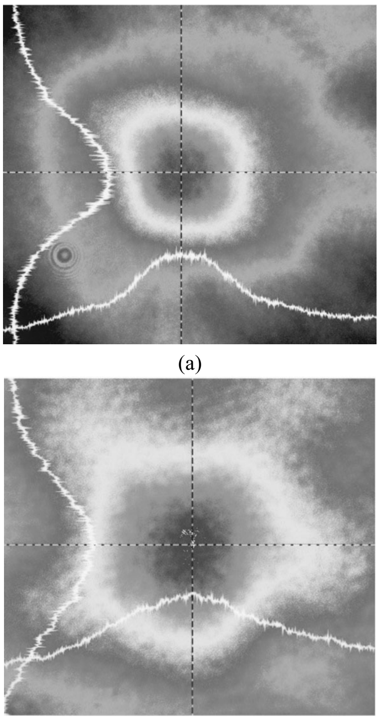


Fig.7 Peak power of Q-switched pulse as a function of incident pump power

The far-field beam spatial profiles of the 1 064 nm CW and Q-switched lasers are measured by using a laser beam analyzer (OPHIR) behind the OC. Fig.8 shows the transverse modes of the 1 064 nm CW and Q-switched lasers corresponding to the pump power of 27.9 W. The Gauss distribution of intensity across the laser beam is obtained owing to the less heat produced in the crystal by using direct pumping method.



(a)

(b)

Fig.8 Transverse modes of 1 064 nm (a) CW and (b) passively Q-switched lasers under the pump power of 27.9 W

In this paper, the direct pumping method is used to the Nd:$Lu_{0.15}Y_{0.85}VO_4$ crystal, whose thermal conductivity is less than half of that of Nd:YAG, for producting 1 064 nm CW and passively Q-switched lasers. The maximum output power of CW operation is 2.8 W, and the maximum average output power of Q-switched pulse is 1.2 W. The repetition rate of 23.69 kHz and the pulse width of 35 ns are obtained at the pump power of 27.9 W. The high-quality fundamental transverse mode can be observed owing to the reduction of thermal effect for Nd:$Lu_{0.15}Y_{0.85}VO_4$ crystal by 885 nm direct pumping.

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