High-Power Passively Q-Switched Nd:YAG Laser at 1112 nm with a Cr^{4+}:YAG Saturable Absorber *

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(Received 6 November 2015)

A high-power passively Q-switched Nd:YAG laser operating at 1112 nm with Cr^{4+}:YAG as a saturable absorber is demonstrated. Under 808 nm diode-direct pumping, the maximum average output power of 2.73 W is achieved at the pump power of 16.65 W, corresponding to an optical-to-optical conversion efficiency of 16.4%. At the same time, the pulse width, pulse repetition rate, single pulse energy and peak power are 27.2 ns, 9 kHz, 303.3 μJ and 11.2 kW, respectively. As far as we know, the result gives the highest average output power at 1112 nm generated by an 808 nm diode-end-pumped Nd:YAG laser.

PACS: 42.55.Xi, 42.60.Gd, 42.70.−a DOI: 10.1088/0256-307X/33/2/024201

In recent years, more and more attention has been paid to 1.10 μm lasers due to their potential applications.[1,2] A 1112 nm laser can be obtained through the $R_2 \rightarrow Y_6$ transition according to Fig. 1,[3] and it has many important applications in laser medical diagnosis, treatment, and scientific research. For example, the 1112 nm laser can be applied in selective photo-ionization in laser chemistry.[4] In addition, a yellow-green 556 nm laser can be generated by frequency doubling, which has many important applications in laser display, atmospheric remote sensing, medical treatment and laser precision manufacture.[5–7]

The comparison of the laser performance[8] at 1064, 946, 1319 and 1112 nm transitions in Nd:YAG is listed in Table 1. Here σ is the stimulated emission cross section, and $\Delta\upsilon$ is the width of transition frequency. According to Table 1, the stimulated emission cross section of 1112 nm is only 0.079, 0.71 and 0.4 times of 1064 nm, 946 nm and 1319 nm, respectively. This ratio indicates a serious mode competition. The stimulated-emission cross section at 1112 nm is only 3.6×10^{-20} cm^2. Thus a small area leads to a high lasing threshold and possibly causes a serious thermal lens effect, and poor beam quality.[3]

Over the past few years, different structures have been utilized to achieve the 1112 nm wavelength laser and the frequency doubling laser. In 1999, Kravtsov *et al.* succeeded in achieving 0.5 W cw operation of a diode-pumped garnet laser at 1112 nm, as well as intracavity conversion of the generated radiation into the second harmonic (λ = 556 nm).[9] In 2006, Jia *et al.* obtained the maximum output power of 0.61 W cw laser under the pump power of 1.6 W by a continuous GaAlAs LD with an emission wavelength of 808 nm.[5] An efficient dual-wavelength laser-diode-pumped Nd:YAG ceramic laser operating at 1112 and 1116 nm was achieved by our group in 2013. In that experiment, we obtained a maximum total output power of 3.43 W including a 1.77 W 1112 nm component and a 1.66 W 1116 nm component under a pump power of 16.1 W.[10] In the same year, our group obtained the 3.37 W 1112 nm cw laser under the pump power of 18.6 W by using a 1.0 at.% Nd-doped ceramic as gain medium.[11]

In most of the previous works, the output power and brightness are still not high enough to achieve the frequency-doubled yellow-green laser satisfactorily. To solve this problem, the resonator cavity was designed into a concave-plane structure, and the lens coating was subtly designed to suppress the strong competing emissions. In addition, the length of the resonator cavity was as short as possible to reduce the loss.

In this experiment, Nd:YAG was used as the laser crystal and Cr^{4+}:YAG was used as the saturable absorber. Nd:YAG single crystal is the most widely used laser gain medium, owing to its good optical quality and high thermal conductivity. Moreover, the physical, chemical and mechanical properties of Nd:YAG matrix lattice are also relatively attractive. From the lowest temperature to the melting point, the structure is very stable.[12,13] The Cr^{4+}:YAG crystal shows good performance as a saturable absorber to generate Q-switched and mode-locked pulses operation from 0.9–1.2 μm.[14] Cr^{4+}:YAG has the advantages of large absorption cross section, moderate excited-state lifetime, high doped-ion concentration, good thermal conductivity, high damage threshold, low saturation intensity, no degradation with time, durability, stable physical and chemical properties. Thus it is considered to

*Supported by the Natural Science Foundation of Shandong Province under Grant Nos ZR2015FM018 and ZR2014FM028, and the National Natural Science Foundation of China under Grant No 61475086.

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be a perfect saturable absorber to obtain high peak power and high repetition rate pulse.[15]

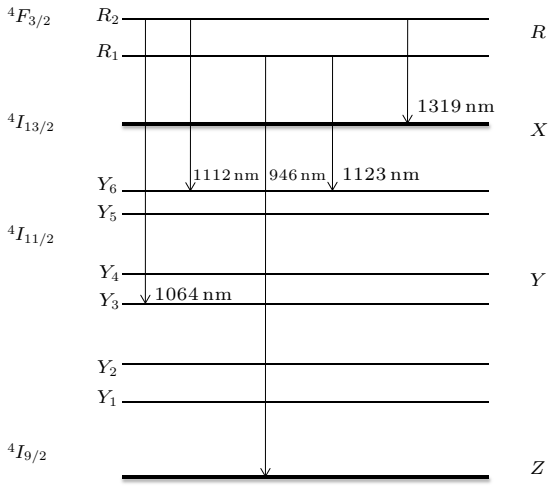


Fig. 1. The energy levels of Nd^{3+} in Nd:YAG.

In this Letter, we investigate the performance of a Cr^{4+}:YAG used for passively Q-switched operation of a diode-end-pumped Nd:YAG laser at 1112 nm. A maximum average output power of 2.73 W is obtained at the pump power of 16.65 W, corresponding to an optical conversion efficiency of 16.4% and a slope efficiency of 29.1%, respectively. The pulse width is 27.2 ns, with a pulse repetition rate of 9 kHz.

After taking the excited state absorption of the saturable absorber and the population reduction of the laser into consideration,[16] the Q-switching requirement is obtained,

$$\frac{\alpha_{\rm a} L_{\rm a}}{\alpha_{\rm g} L_{\rm g}} \frac{\sigma_{\rm a} A_{\rm g}}{\sigma_{\rm g} A_{\rm a}} > \frac{\gamma}{1-\beta}, \tag{1}$$

where $\alpha_{\rm a}$, $L_{\rm a}$, $\sigma_{\rm a}$, and $A_{\rm a}$ are, respectively, the small-signal absorption coefficient, length, absorption cross section, and effective beam area of the saturable absorber, and $\alpha_{\rm g}$, $L_{\rm g}$, $\sigma_{\rm g}$, and $A_{\rm g}$ are, respectively, the small-signal gain coefficient, length, gain cross section, and effective beam area of the laser crystal.

The population reduction factor of γ equals to one for an ideal four-level laser, and β equals to 0.1–0.2 according to Ref. [17]. Assuming that the value of β is 0.1, the fractional at the right of the inequality equals to 1.11. Under normal circumstances, the first term in Eq. (1) is close to unity. In our experiment, the intracavity focusing is not used, that is, $A_{\rm g} \approx A_{\rm a}$, then the absorption cross section $\sigma_{\rm a}$ of the saturable absorber must be larger than the emission cross section of the laser gain medium $\sigma_{\rm g}$. According to Table 1, $\sigma_{\rm g}$ equals to 3.6×10^{-20} cm^2, and the value of $\sigma_{\rm a}$ equals to 4.3×10^{-18} cm^2 the same as Ref. [17]. Obviously, $\sigma_{\rm a}$ is far greater than $\sigma_{\rm g}$. Thus the passively Q-switched Nd:YAG laser at 1112 nm with a Cr^{4+}:YAG saturable absorber could be achieved.

Table 1. The comparison of the performance among the main laser transitions of Nd:YAG.

λ (nm)	Transition	σ (10×10^{-20} cm^2)	$\Delta\upsilon$ (cm^{-1})	Relative performance
1064	R_2–Y_3	45.8	5	100
946	R_1–Z_5	5.1	9	46
1319	R_2–X_1	8.9	6	34
1112	R_2–Y_6	3.6	14	49
1123	R_1–Y_6	3.0	13	40

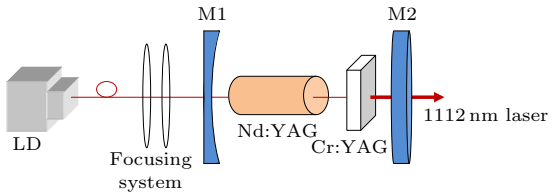


Fig. 2. Experimental setup for the 1112 nm laser.

The experimental setup of the passively Q-switched Nd:YAG 1112 nm laser is shown in Fig. 2. A 30 W 808 nm fiber-coupled cw laser diode (LD) (NA=0.12, dcore=600 μm) was used as the pumping source. The pump beam was re-imaged by focusing the optical system into the laser crystal, and the waist diameter is about 300 μm. The resonator cavity was designed into a concave-plane structure with the length of 20 mm. M1 was a concave mirror with a curvature radius of 300 mm and it was anti-reflection coated at 808 nm on the plane face, high-reflection at 1112 nm on the other face. The output coupler M2 was a plane mirror which had a transmission of 1.2% at 1112 nm. Both mirrors were coated with transmission higher than 95% for 946 nm, 1064 nm and 1319 nm to suppress the strong competing emissions. A traditional Nd:YAG crystal with Nd^{3+}-doped concentration of 1.0 at.% and $\Phi4\times8$ mm^3 dimensions was used to be the gain medium. Both ends of the laser crystal were anti-reflection coated for 1112 nm and 808 nm. The laser crystal was wrapped with indium foil and mounted in a copper block cooled by water at a constant temperature of 20℃. The Cr^{4+}:YAG is employed as a saturable absorber in our experiment with the initial transmission of 95%. The output power was measured by a power meter (Molectron PM10) connected to a Molectron EPM2000. The pulse width and repetition rate of the laser pulses were recorded by an Infiniium DSO90804A digital storage oscilloscope (8 GHz bandwidth, 40 G samples/s) and a fast PIN

photodiode.

For a fiber-coupled laser diode, the thermal focal length can be expressed as Ref. [18] and the cavity mode size in the gain medium is given by Ref. [19]. The parameters used in the calculation are listed in Table 2. Taking the above-known data into the equation, the TEM00 at the Nd:YAG crystal is calculated in the range 313–384 μm.

Table 2. Parameters for calculation of the cavity mode size.

Parameters	Value
dn/dT: thermal-optic coefficient	$7.3\times10^{-6}\,\mathrm{K}^{-1}$
n: refractive index	1.82
α_T: thermal expansion coefficient	$7.8\times10^{-6}\,\mathrm{K}^{-1}$
α: absorption coefficient	$4.1\,\mathrm{cm}^{-1}$
K_c: thermal conductivity at 20℃	$13\,\mathrm{Wm}^{-1}\mathrm{K}^{-1}$
L_c: length of the crystal	10 mm
ξ: thermal conversion coefficient	0.3
ω_p: pump laser beam radius	0.3 mm

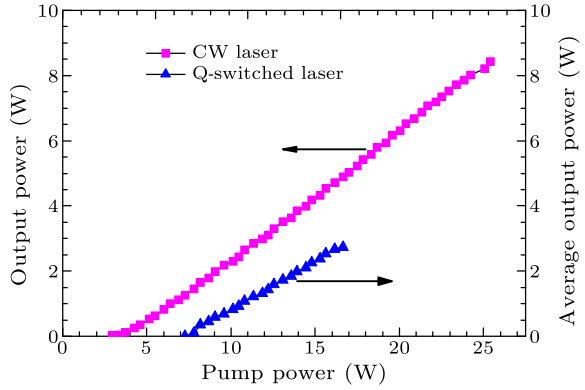


Fig. 3. The output power at 1112 nm versus the pump power.

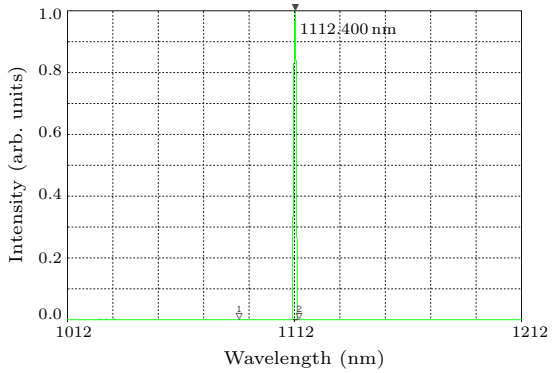


Fig. 4. The laser emission spectrum of the Nd:YAG laser.

First, the cw performance of the laser operating at 1112 nm was studied without Cr^{4+}:YAG. To reduce the thermal lens effect as much as possible, the length of cavity is the shorter the better. A maximum output power of 8.43 W was achieved under a pump power of 25.41 W, corresponding to an optical-to-optical conversion efficiency of 33.2% and a slope efficiency of 37.5%. The threshold was 2.94 W. Figure 3 describes the characteristics of the pump power and output power about the cw laser.

Next, when the Cr^{4+}:YAG is inserted into the cavity as a saturable absorber, the 1112 nm Q-switched pulse will be obtained successfully. Under the pump power of 16.65 W, the maximum average output power of 2.73 W is achieved, corresponding to an optical-to-optical conversion efficiency of 16.4% and a slope efficiency of 29.1%. The dependence of the average output power on the pump power is also shown in Fig. 3. According to Fig. 3, the laser threshold of the cw laser is lower than the Q-switched laser. This is due to the high loss in the Q-switched laser cavity before Cr^{4+}:YAG reaching saturation. In addition, the emission spectrum of the laser is measured by an optical spectrum analyzer (Yokogawa AQ6315A) in the range from 350 to 1750 nm. Figure 4 is the detection results. As we can see, the wavelength emitted by the laser is 1112 nm, and no other wavelengths appear.

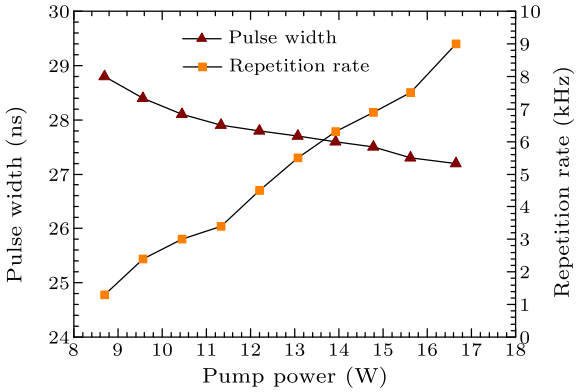


Fig. 5. The pulse repetition rate and pulse width versus the pump power.

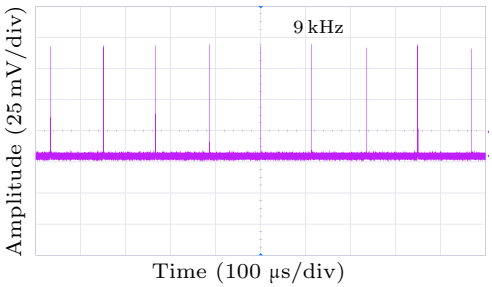


Fig. 6. A typical pulse train of the Q-switched laser.

The corresponding pulse width and repetition rate as a function of the pump power are shown in Fig. 5. With the increase of the pump power, the pulse width decreases to 27.2 ns slowly and the repetition rate changes from 1.3 kHz to 9 kHz simultaneously. The pulse width of 27.2 ns and the maximum repetition rate of 9 kHz are obtained under the pump power of 16.65 W. A typical oscilloscope trace with the pulse repetition rate of 9 kHz and a temporal pulse shape with the width of 27.2 ns are shown in Figs. 6 and 7, respectively.

It is known to all that the thermal lens effect brings down the quantum efficiency and it makes the laser threshold increase and laser efficiency decrease. At the pump power of 16.65 W, the thermal lens effect is too large to increase the laser efficiency, and at this moment we obtain the highest average output power.

In addition, in the case of high pumping power, there will be a tail pulse with wide pulse width and low peak power after the output of the single laser pulse, as shown in Fig. 8. This phenomenon will be explained in the following.

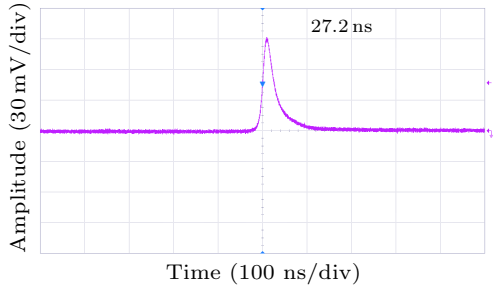


Fig. 7. A typical Q-switched laser pulse.

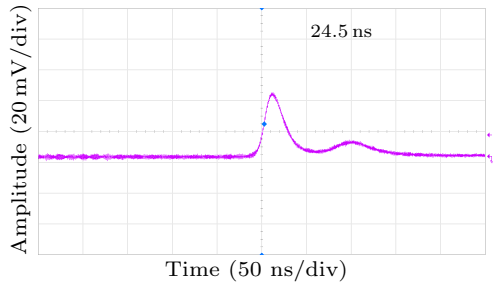


Fig. 8. Tail pulse phenomenon.

Due to the long lifetime of the Cr^{4+}:YAG upper level, when the Cr^{4+}:YAG is bleached and a laser pulse is generated, the Cr^{4+}:YAG which still has high transmission rate and small corresponding loss is not fully restored. On the other hand, owing to the fact that the pulse width of the Q-switching pulse is far less than that of the laser lower level lifetime, when a Q-switching laser pulse is finished, there are a large number of particles at the laser lower level, while most of the particles return to the ground state by spontaneous emission soon, making the number of particles at lower level few or about 0. In this process, the number of particles at upper level reduces to be very small by spontaneous emission. On the contrary, the number of particles increases due to pumping, and the number of the laser inversion particles is greater than the threshold value again, thus another small pulse is generated.

In conclusion, with Cr^{4+}:YAG as a saturable absorber, a passively Q-switched Nd:YAG laser operating at 1112 nm is achieved. In cw operations, the maximum output power is as high as 8.43 W. In the passively Q-switched operation, the maximum average output power of 2.73 W is obtained, corresponding to an optical-to-optical conversion efficiency of 16.4% and a slope efficiency of 29.1%. The corresponding pulse width, pulse repetition rate, single pulse energy and peak power are 27.2 ns, 9 kHz, 303.3 μJ and 11.2 kW, respectively.

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