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Laser performance of monolithic Cr,Nd:YAG self-Q-switched laser

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Abstract

The self-Q-switched laser performance of monolithic Cr^{4+},Nd^{3+}:YAG concave-planar resonator with 5-mm length was studied experimentally and theoretically. The slope efficiency is as high as 24% and pump threshold is as low as 64 mW. The pulse width, the single pulse energy and the pulse repetition rate of monolithic Cr,Nd:YAG self-Q-switched laser were measured as a function of absorbed pump power. With the increase of pump power, the pulse width decreases and the pulse energy and the pulse repetition rate increase. The average output power of 91 mW with pulse width of 7 ns at repletion rate of 35.5 kHz was obtained at the maximum absorbed pump power of 440 mW, the peak power is as high as 370 W. The theoretical prediction of pulse energy, pulse width and pulse repetition rate as a function of absorbed pump power based on rate equations is in a good agreement with our experimental data. This can lead to develop the diode laser-pumped monolithic self-Q-switched solid-state microchip lasers.

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Keywords: Cr,Nd:YAG crystal; Self-Q-switched laser; Saturable absorber

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1. Introduction

In recent years, Cr^{4+}-doped crystals have attracted a great deal of attention as passive Q-switches [1–8] in comparison with previously used saturable absorbers, such as dyes [9] and LiF:F_2^- color center crystals [10]. Cr^{4+}-doped crystals are more photochemically and thermally stable, have a higher damage threshold and large absorption cross-section, low saturable intensity and high damage threshold. Especially, Cr^{4+}-doped YAG crystal, owing to its easy growth of high quality and high concentration single crystal and can be co-doped with gain medium to form self-Q-switched laser crystals [5,11–14], has attracted a great deal of interest in recent years. Zhou and

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co-workers [5,11–14] first studied the self-Q-switched laser performance of LD-pumped Cr,Nd:YAG crystal, the pump source they used is the quasi-CW mode AlInGaAs diode laser. Using different laser cavities, they obtained the Q-switched pulse energy of 7 μJ and an FWHM duration of 3.5 ns [5], pulse energy of 10 μJ and an FWHM duration of 3.5 ns [11], pulse energy of 3 μJ and a FWHM duration of 30 ns, and pulse energy of 8 μJ and an FWHM duration of 270 ps [14], respectively. The highest net optical conversion efficiency they obtained using different laser cavities is 8%. Dong et al. [15] also reported the LD-pumped Cr,Nd:YAG self-Q-switched laser, but the optical conversion efficiency is about 13% and slope efficiency is 20%. Dong et al. [16] have reported the high efficiency output of Cr,Nd:YAG self-Q-switched laser, the optical conversion efficiency is as high as 21.6% and the slope efficiency is 26%. It is well known that the distribution coefficient of Nd^{3+} ions in YAG is about 0.18, so the concentration of Nd in YAG cannot be high and if the concentration is higher than 1 at.%, the distribution of Nd along the radius and growth axe is not unity. This will degrade the laser performance of Cr,Nd:YAG crystal. So growth of high quality Cr,Nd:YAG crystals is very essential to obtain good laser performance. In this paper, we present the performance of Ti:sapphire laser-pumped monolithic Cr,Nd:YAG self-Q-switched laser. The single pulse energy, the pulse width and repetition rate of 1064 nm laser have been measured as a function of absorbed pump power. Meanwhile, the coupled equations of self-Q-switched laser were given and the numerical solutions of the equations agree with the experimental results in entire pump region.

2. Experiments

The Cr,Nd:YAG crystal used in the experiment was grown by using the standard Czochralski (CZ) method. Cr^{4+} is regarded to be substituted into distorted tetrahedral Al site, therefore a charge compensator is required and $CaCO_3$ was added to as a charge compensator. The nominal concentrations of Cr and Nd in Cr,Nd:YAG crystal are 0.01 and 1 at.%, respectively. The absorption spectra were measured using a Cary 500 Scan UV–Vis–NIR spectrophotometer at room temperature (298 K).

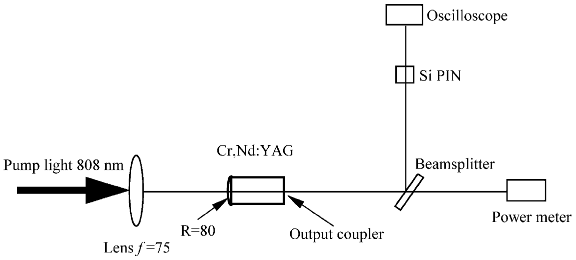

Fig. 1. The experimental setup of Ti:sapphire laser-pumped Cr,Nd:YAG self-Q-switched laser.

The schematic of CW Ti:sapphire laser-pumped Cr,Nd:YAG self-Q-switched laser cavity is shown in Fig. 1. A Cr,Nd:YAG crystal was polished to a concave-planar geometry as a laser resonator. The concave mirror has a radius of curvature of 80 mm and is coated for high transmission at 808 nm and total reflection at 1064 nm. The planar surface is coated for 95% reflection at 1064 nm as the output coupler and total reflection at 808 nm. The overall cavity length is 5 mm. The misalignment of the axes of the two mirrors is measured to be less than 0.3°. The laser operation was performed at 278 K by using the constant-temperature water-cooled circulation with a copper surface. The Q-switched pulses were recorded using a fast Si PIN detector with a 1.5 ns rise time and a Tektronix TDS 380 digitizing oscilloscope with 400 MHz sampling rate in the single-shot mode. The output power was measured using a laser power meter. The Ti:sapphire laser output, after beam shaping with a focal lens, is focused onto a spot with a diameter of 50 μm. The Ti:sapphire laser is operated in the CW mode, and after focal lens the loss is approximately 8%.

3. Results and discussion

The room temperature absorption spectrum of Cr,Nd:YAG crystal is showed in Fig. 2. In Cr-doped YAG crystal, there are several valent states of Cr ions, Cr^{3+} is the dominant state, Cr^{4+} can be formed in Cr-doped YAG crystal by adding Ca^{2+} compensation charge and YAG crystal growing in

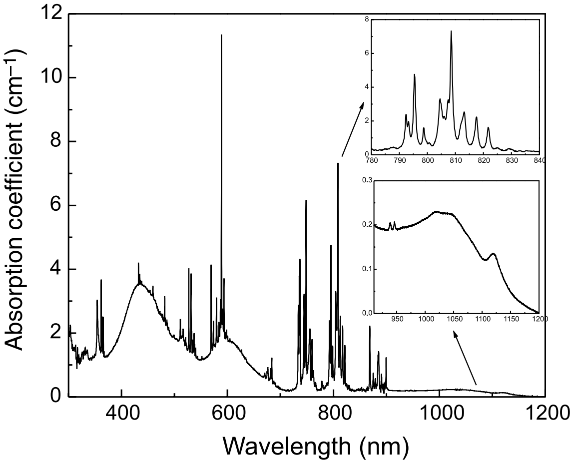

Fig. 2. The absorption spectrum of Cr,Nd:YAG crystal at room temperature.

oxygen atmosphere. But Cr^{4+} is only a small fraction (about 4% [17]) of total Cr ions added in Cr,Nd:YAG crystal. The absorption spectrum of Nd^{3+} is superimposed over that of Cr^{3+}, there is a broad absorption spectrum of Cr^{4+} centered at 1.06 μm. The absorption coefficient is 7.3 cm^{-1} at the pumping wavelength of 808 nm for Nd^{3+} ions and is 0.23 cm^{-1} at 1064 nm for Cr^{4+}. The emission cross-section is 2.35×10^{-19} cm^2 [16] at 1064 nm, the lifetime is about 210 μs, a little shorter than that of Nd:YAG (230 μs).

With Cr,Nd:YAG crystal as the active medium, under the CW pumping, the repetitively Q-switched laser was obtained. The average output power, pulse repetition rate and pulse width (FWHM) in a self-Q-switched mode were measured as functions of the absorbed pump power. The pulse energy was determined from the average output power and pulse repetition rate. The peak power was determined from the pulse energy and pulse width. Fig. 3 shows the average output power, pulse energy and peak power of Cr,Nd:YAG self-Q-switched laser as a function of the absorbed pump power. It can be seen that the average output power depends linearly on the absorbed pump power, and there is no saturation, so high power laser output can be obtained by using high power diode laser as pumping source. Form the linear relationship of average output power and the absorbed pump power, the threshold pump power and slope efficiency can be extrapolated. The threshold pump power is approximately 64 mW and the slope efficiency is 24.1%. And the optical efficiency (the ratio of average output power and the incident pump power) of the self-Q-switched laser is approximately 20.6%. The highest average output power of 91 mW at 1064 nm is obtained at an absorbed pump power of 440 mW. We obtained 2.56 μJ self-Q-switched pulses with a pulse width of 7 ns, resulting in a peak power of 370 W at a repetition rate of 35.5 kHz at 440 mW absorbed pump power (Fig. 3).

Fig. 4 shows the pulse repetition rate and the pulse width as functions of the absorbed pump power. The pulse repetition rate (*f*) and pulse width (t_p) are another two important parameters of passively Q-switched lasers. The incident pump power has a perceptible effect on the pulse repetition rate, the pulse width of the self-Q-switched laser. The repetition rate increases linearly with the increasing absorbed pumping power, as expected

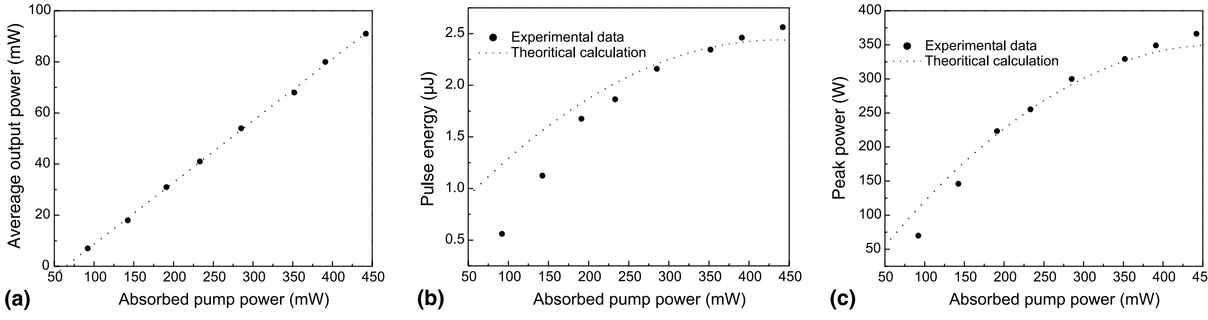

Fig. 3. Average output power, pulse energy and peak power versus absorbed pump power of Cr,Nd:YAG self-Q-switched laser.

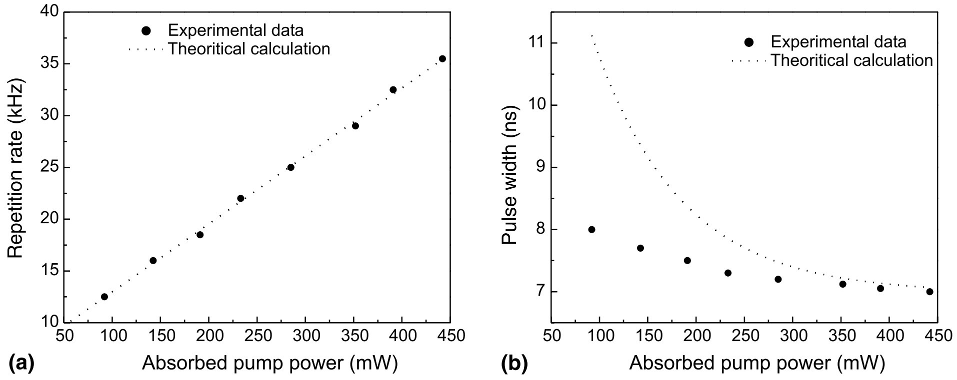

Fig. 4. Repetition rate and pulse width versus the absorbed pump power Cr,Nd:YAG self-Q-switched laser.

from the passively Q-switched theory. The pulse width decreases with the increasing absorbed pump power, and pulse width keeps nearly the same value of 7 ns at the higher absorbed pump power. Fig. 5 shows a typical single self-Q-switched laser pulse with energy of 2.56 μJ and a pulse width of 7 ns at pulse repetition rate of 35.5 kHz at the maximum absorbed pump power of 440 mW, the corresponding peak power is 370 W.

The coupled rate equations of photon density in the self-Q-switched resonator, which includes the excited-state absorption of the saturable absorber and the population reduction factor of the laser, are as follows [18,19]:

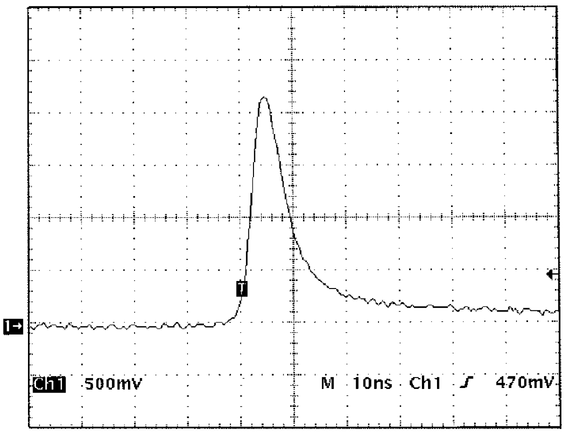

Fig. 5. Oscilloscope trace of a single self-Q-switched laser pulse with a pulse width of 7 ns at 35.5-kHz repetition rate at absorbed pump power of 440 mW.

$$\frac{\mathrm{d}\phi}{\mathrm{d}t}=\frac{\phi}{t_\mathrm{r}}\left(2\sigma n l-2\sigma_\mathrm{g}n_\mathrm{g}l_\mathrm{s}-2\sigma_\mathrm{e}n_\mathrm{e}l_\mathrm{s}-\ln\left(\frac{1}{R}\right)-L\right), \tag{1}$$

$$\frac{\mathrm{d}n}{\mathrm{d}t}=-\gamma\sigma c\phi n-\frac{n}{\tau}+W_\mathrm{p}, \tag{2}$$

$$\frac{\mathrm{d}n_\mathrm{g}}{\mathrm{d}t}=-\sigma_\mathrm{g}c\phi n_\mathrm{g}+\frac{n_{\mathrm{s}0}-n_\mathrm{g}}{\tau_\mathrm{s}}, \tag{3}$$

$$n_\mathrm{g}+n_\mathrm{e}=n_{\mathrm{s}0}, \tag{4}$$

where ϕ is the photon density in the laser cavity of optical length l', n is the population inversion density of the laser rod, σ is the stimulated emission cross-section of the laser crystal, t_r is the cavity round-trip time, $t_\mathrm{r}=2n_1 l/c$, n_1 is the refractive index of the laser crystal, l is the length of the laser crystal, c is the speed of the light, σ_g is the absorption cross-section of ground state of the saturable absorber, σ_e is the absorption cross-section of the excited state, l_s is the length of the saturable absorber, for Cr,Nd:YAG self-Q-switched laser crystal, $l_\mathrm{s}=l$, n_g and n_e are the absorber ground state and excited state population density, respectively, $n_{\mathrm{s}0}$ is the total population density of the saturable absorber, R is the reflectivity of the output coupler, L is the nonsaturable intracavity round-trip dissipative optical loss, γ is the inversion reduction factor, $\gamma=1$ for Nd-doped four-level solid-state lasers, W_p is the volumetric pump rate into the upper laser level and is proportional to the CW pump power and τ is the lifetime of the upper laser level in the gain medium, τ_s is the excited-state lifetime of saturable absorber.

With CW pumping, the laser will be passively Q-switched as soon as the gain exceeds the combined saturable and unsaturable losses in the resonator. As the incident pump power is increased, the laser eventually reaches a threshold condition and begins to repetitively Q-switch with a time interval between pulses, t_c. The pulse energy and pulse repetition rate will be increased and the pulse width will be decreased with further increasing of the incident pump power.

For CW-pumped repetitive Q-switching laser at a repetition rate f, the maximum time available for the inversion to build up between pulses is $t_c = 1/f$. Therefore, the initial inversion density of the Q-switch under the influence of the absorbed pump power can be written as [9]: $n_i = n_{CW} - (n_{CW} - n_f)\exp(-1/\tau f)$ in order to have the inversion return to its original value after each Q-switch cycle, where n_{CW} is the CW pumping inversion density inside the resonator, $n_{CW} = W_p\tau$, W_p is the volumetric pump rate into the upper laser level and is proportional to the CW pump power, $W_p = P_p/h\nu_p A_p l$, P_p is the incident pump power, $h\nu_p$ is the pump photon energy, A_p is the pump beam area and l is the length of the gain medium.

The internal optical loss of the laser resonator can be determined by using the logarithm of reflectivity of the different output couplers and the threshold pump power for each output coupler, described as follows [9]:

$$-\ln R = 2k\mathrm{P}_{th} - L, \tag{5}$$

where R is the reflectivity of the output coupler, k is the pumping coefficient, and P_{th} is the threshold pump power. The internal optical loss of self-Q-switched Cr,Nd:YAG resonator studied here is estimated to be $L = 0.0323$, which was determined in [16] and is used here to stimulate the theory calculation of this self-Q-switched Cr,Nd:YAG laser.

The output pulse energy E, peak power P and pulse width τ_p of self-Q-switched Cr,Nd:YAG laser can be written as [20]:

$$E = \frac{h\nu A}{2\sigma\gamma}\ln\left(\frac{1}{R}\right)\ln\left(\frac{n_i}{n_f}\right), \tag{6}$$

$$P = \frac{h\nu A l}{\gamma t_r}\ln\left(\frac{1}{R}\right)\left\{n_i - n_t - n_{t0}\ln\left(\frac{n_i}{n_t}\right) - (n_i - n_{t0})\left[1 - \left(\frac{n_t}{n_i}\right)^{\alpha}\right]\frac{1}{\alpha}\right\}, \tag{7}$$

$$\tau_p \approx \frac{E}{P}, \tag{8}$$

where $h\nu$ is the photon energy, A is the active area of the laser beam in the laser medium, n_i, n_t and n_f are the population inversion densities at the start of Q-switching, the point of maximum power and the end of the Q-switched pulse, respectively; α is a synthetic dimensionless parameter, $\alpha = \sigma_g/\gamma\sigma$, n_{t0} corresponds to the n_t in the case of $\alpha \to \infty$,

$$n_{t0} = \left\{n_{th}\left(\ln\left(\frac{1}{R}\right) + \left(\frac{\sigma_e}{\sigma_g}\right)\ln\left(\frac{1}{T_0^2}\right) + L\right)\right\} \Bigg/ \left\{\ln\left(\frac{1}{R}\right) + \ln\left(\frac{1}{T_0^2}\right) + L\right\},$$

where n_{th} is the population inversion density at threshold,

$$n_{th} = \left\{\ln\left(\frac{1}{R}\right) + \ln\left(\frac{1}{T_0^2}\right) + L\right\} \Bigg/ \{2\sigma l\},$$

T_0 is the initial transmission of the saturable absorber.

Eqs. (6) and (7) contain three unknown variables, n_i, n_f and n_t. These unknown variables can be obtained through numerical solving of Eqs. (1)–(3), the related parameters used in the numerical solution of Eqs. (1)–(3) are listed in Table 1. The dotted lines in Figs. 3(b) and 4(b) show the calculated values of the single pulse energy and the pulse width as a function of the absorbed pump power, respectively. It can be seen from Figs. 3(b) and 4(b) that the theoretical calculations are in fair agreement with the experimental results. From the theoretical calculations and the experimental results, we can see that the laser characteristics of the self-Q-switched Cr,Nd:YAG laser depend strongly on the absorbed pump power. With the increase of the absorbed pump power, the pulse energy increases and the pulse width decreases. However, there are also some discrepancies between the calculations and the experimental results, especially at the lower absorbed pump power, with the

Table 1
The parameters for calculating the theoretical results

σ_g	4.3×10^{-18} cm^2 [20]
σ_e	8.2×10^{-19} cm^2 [20]
σ	2.35×10^{-19} cm^2 [16]
τ	210 μs [16]
τ_s	3.4 μs
γ	1
T_0	90%
l	0.5 cm
A	3.925×10^{-5} cm^2
t_r	0.607 ns
L	0.0323
$h\nu_p$	2.46×10^{-19} J
$h\nu$	1.86×10^{-19} J

decrease of the absorbed pump power, the difference between the calculated pulse energy and measured pulse energy increases, so is the difference between the calculated pulse width and the measured pulse width. This is because the uniform excitation in the gain medium is assumed in the theoretical analysis. In fact, it is impossible to achieve in practice, the pump beam area will vary at different absorbed pump powers, and the population inversion density will vary with distance from the cylinder axis. Therefore, the effective pump area will be bigger at lower pump power level than that at high pump level. Another cause of this difference between calculated results and the experimental results may be caused by the unsturable loss at lower pump level that is higher than that at higher pump level. This is attributed to the nonlinear absorption nature of saturable absorber, Cr^{4+}, the higher the lasing intensity, the lesser unsturable loss. Also the related parameters in Table 1 used for calculation are not well known, such as the ground absorption cross-section and the excited state absorption cross-section of Cr^{4+} in YAG crystals.

According to the theoretical analysis, when the pump power is well in excess of the pump threshold, the pulse repetition rate, f, should increase linearly with the pump power, and the pulse repetition rate of a continuously pumped passively Q-switched laser can be written as [20]:

$$f = \left[\tau \ln \frac{(W_p/W_{p_{th}}) - \beta}{(W_p/W_{p_{th}}) - 1}\right]^{-1}, \tag{9}$$

where $\beta = 1 - (f_a/\gamma)(1 - n_f/n_i)$, $W_{p_{th}} = n_i/\tau$, W_p corresponds to the population density pumped to the upper laser level per unit time, $W_{p_{th}}$ is the threshold of W_p, τ is the upper level laser lifetime. The numerical solutions of Eqs. (1)–(3) may obtain a train of laser pulses under the CW pump power, from Eq. (9), the pulse repetition rate can be calculated for different absorbed pump power. The dotted lines in Fig. 4(a) show the calculated pulse repetition rate versus the absorbed pump power. From Fig. 4(a), we can see that the experimental results agree well with the prediction of the theoretical calculation.

4. Conclusion

In conclusion, the high efficient laser performance of self-Q-switched laser in the co-doped Cr^{4+},Nd^{3+}:YAG monolithic concave-planar resonator with 5-mm thickness was demonstrated. The slope efficiency is as high as 24.1% and the pump threshold is as low as 64 mW. And the high average output power of this monolithic Cr,Nd: YAG self-Q-switched laser can be obtained by using high power laser diode as pumping source. The pulse width, the single pulse energy and the pulse repetition rate were measured under the influence of the absorbed pump power, the average output power of 91 mW with pulse width of 7 ns at repletion rate of 35.5 kHz was obtained at the maximum absorbed pump power of 440 mW, the peak power is as high as 370 W. And the experimental results agree with the numerical calculations of the passively Q-switched rate equations. For this kind of the monolithic laser cavity design, we can put a second harmonic generator such as KTP or KDP crystals at the end of the laser cavity, to realize the frequency-doubling, so that this can lead to develop the diode laser-pumped compact monolithic self-Q-switched solid-state lasers.

Acknowledgements

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