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Laser-diode-pumped Cr^{4+}, Nd^{3+}:YAG self-Q-switched laser with high repetition rate and high stability

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ABSTRACT A diode end-pumped self Q-switched Cr^{4+}, Nd^{3+}: YAG laser was established with 30-ns pulse width (FWHM) and 0.5-μJ pulse energy output. In normal pulse pumping operation, the lasing threshold changed greatly from 122 mJ to 2.4 mJ as the pump pulse frequency varied from 1 Hz to 500 Hz due to pumping-induced thermal effect. A pre-pumping method was proposed and the change of the lasing threshold was reduced; programmable Q-pulse output with maximum frequency of 16 kHz and high stability was achieved.

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1 Introduction

Cr^{4+}:YAG crystals, due to their advantages of high damage threshold, good heat conductivity, stable optical and chemical characteristics and long lifetime, have been widely used as saturable absorbers in flashlamp-pumped oscillators and MOPA systems, as well as in diode-pumped solid-state lasers to generate passively Q-switched or mode-locked laser pulses [1–4]. In 1992 a codoped Cr^{4+}, Nd^{3+}:YAG crystal, which combined the gain medium and the saturable absorber, was used to generate self-Q-switched highly polarized pulse output [5]. Soon a diode-pumped monolithic Cr^{4+}, Nd^{3+}:YAG laser was reported [6]. In 1994 a microchip laser, which was constructed from thin pieces of Nd^{3+}:YAG bonded to thin pieces of Cr^{4+}:YAG, produced Q-pulse output of 337 ps duration at the repetition rate of 6 kHz [7]. In the running of a diode-pumped self-Q-switched Nd:YAG laser with Cr^{4+} absorber reported, LD cw and pulse-pumping mode were generally used. In cw mode, one can obtain a higher repetition rate output than that in a pulse-pumping mode at the same pump peak power. But the repetition rate of the output was unstable and uncontrollable, and the Q-pulse has a larger intensity fluctuation as well. The output pulse, which has a frequency consistent with the pump, can be realized in LD pulse-pumping mode. But the inversion density of residual populations in the cavity, the recovery time of the saturable absorber and the thermal effect of the crystal gave rise to the instability of Q-switching with respect to different pump frequencies. In this paper, by using a pre-pumping technique, we achieved programmable self-Q-switched laser at 1064 nm wavelength with high frequency up to 16 kHz and high stability in Cr^{4+}, Nd^{3+} codoped YAG crystal. Thus the self-Q-switched lasers may be used in laser-image radar and free-space communication.

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2 Experimental

The experimental setup of the LD end-pumped Cr^{4+}, Nd^{3+}:YAG laser is shown in Fig. 1. A 4-W laser diode (SDL-2382-P1, emitting area $1 \times 500\,\mu m$) was used as the pumping source, which can be operated in cw or pulse pattern. An aspheric lens L_1 and a spherical lens L_2 focused the emission from the diode on the Cr^{4+}, Nd^{3+}:YAG disk crystal ($\Phi = 6 \times 1.5$ mm), the measured coupling efficiency was 80%. One surface of the crystal, as the cavity's input mirror, was coated with high-reflection film at 1064 nm and high-transmission film at 808 nm, while the other side of the crystal had an anti-reflection coating at 1064 nm to reduce the loss in the cavity. A mirror OC of 0.5% transmission at 1064 nm was used as the output coupler. The overall cavity length was 25 mm. The filter F filtered the laser at 808 nm and transmitted 80 percent of the light at 1064 nm.

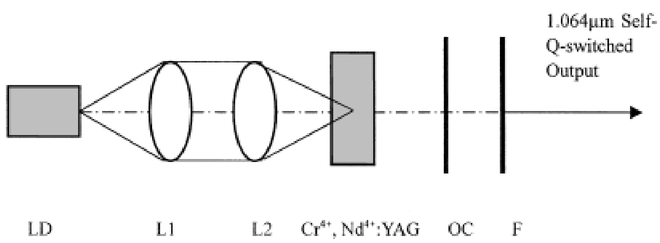

FIGURE 1 Experimental setup of LD end-pumped Cr^{4+}, Nd^{3+}:YAG laser

3 Results

3.1 *LD cw pumping*

In LD cw pumping operation, a self-Q-switched laser pulse series at 1064-nm wavelength was obtained. The measured lasing power threshold was 2.13 W (LD' output power not considering the coupling loss). Figure 2 describes

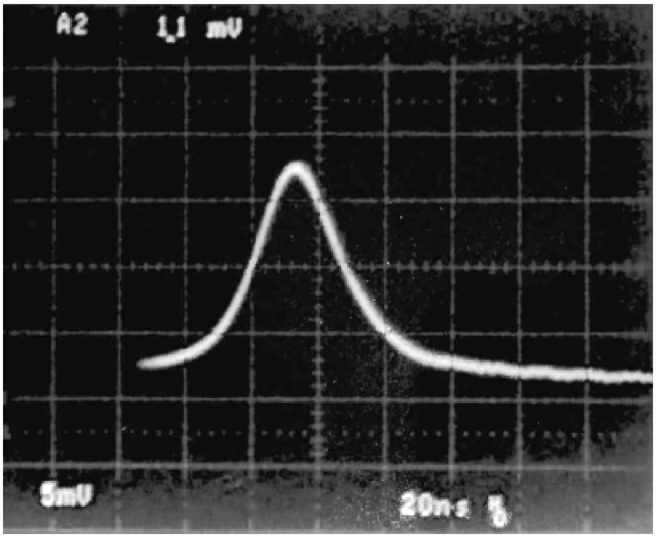

FIGURE 2 Q-switched pulse shape with FWHM duration of 30 ns

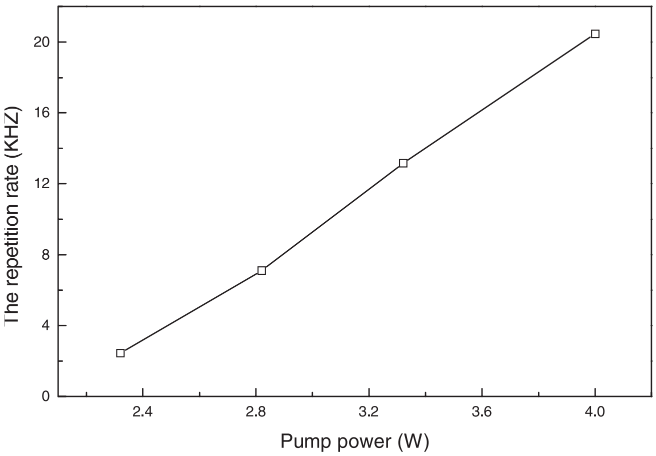

FIGURE 3 The relationship between the pump power and Q-pulse repetition rate

a Q-switched pulse with FWHM duration of 30 ns, 0.5 μJ single pulse energy measured. Figure 3 shows the relationship between the pump power and the Q-pulse repetition rate. The repetition rate rose from 2.44 kHz to 20.45 kHz when the pump power was increased from 2.32 W to 4 W.

3.2 *LD rectangular pulse pumping*

Q-switched output with single pulse energy of 0.5 μJ and pulse width of 30 ns was also obtained in LD rectangular pulse pumping operation. The minimum pumping pulse duration, for which the laser threshold was reached, was measured at a fixed pump frequency of 100 Hz at different pump powers (LD peak powers). The results are displayed in Table 1. It is clear that, due to the increase of pumping rate with the pump power, the minimum pumping pulse duration needed for lasing decreased. Multi-Q-pulses can be achieved in every pump pulse by increasing the pump power or pulse duration.

In addition, the relationship between the minimum pumping pulse duration needed for lasing and the pump frequency at the fixed pump peak power of 2.68 W are shown in Table 2.

Pump power (W)	2.10	2.42	2.58	2.77	2.97	3.19	3.41
Pulse duration (ms)	6.1	4.6	4.0	3.4	3.0	2.6	2.3

TABLE 1 The minimum pumping pulse duration needed for lasing at different pump power

Pump frequency (Hz)	1	2	5	10	20	50	100	200	500
Pulse duration (ms)	57	49	31	20	13.8	7.2	4.2	2.4	1.1

TABLE 2 The minimum pumping pulse duration needed for lasing at different pump frequencies

From Table 2 we surprisingly found that: (i) at low pump frequency the minimum pumping pulse duration is two orders of magnitude larger than the lifetime of Nd^{3+} at upper energy level (about 230 μs); (ii) the minimum pumping pulse duration varies greatly with the pump frequency. The lasing energy threshold E_{Thr}, which can be calculated by (1), decreased from 122 mJ to 2.4 mJ as the pump frequency was increased from 1 Hz to 500 Hz.

$$E_{Thr} = \eta_C \times P_R \times T_{Min} \tag{1}$$

in which η_C is the coupling efficiency of LD, P_R is the rectangular peak power, and T_{Min} is the minimum pumping pulse duration.

These results can be attributed to thermal effects of the crystal induced by pump energy. The explanation is as follows: under a given pump power density such as LD rectangular pulse pumping, the gain of the laser cavity will reach a level and remain invariable after a certain pumping duration (a little longer than the lifetime of Nd^{3+} at upper energy level). If the loss of the cavity is constant and the gain is smaller than the loss, the laser emission will never be obtained. But the cavity did lase after 57 ms LD pumping duration at 1 Hz pump frequency – a great part of the pump energy is transformed into heat, which results in the formation of a thermal lens with a focal length of f_T in the crystal. The more the pump energy is transformed, the less the focal length is [8]. So in fact the laser of a flat–flat resonator behaved, to a great extent, as though it is formed with a planar–concave cavity in which the radius of curvature of the concave lens is $2f_T$. Following the ABCD ray-transfer matrix procedure, we have worked out the stability condition. The results show that the resonator remains stable until the thermal focal length (f_T) decreases to less than the cavity length L from ∞. In general, the thermal lens plays the role of stabilizing the resonator and results in the decrease of diffraction loss. As the heat produced by pumping increases, the thermal effect gets stronger and the mode loss reduces, that is to say, the threshold gets smaller as long as f_T is bigger than L. In the experiment, due to the low cavity gain, the loss changes to gain, which produces Q-pulse only under a certain thermal lens effect. This is why the pumping pulse duration needed for lasing is much longer than the lifetime of Nd^{3+} at upper levels and the laser threshold with respect to pumping pulse duration depends on the pump frequency. Therefore the pump-energy-induced thermal effect played an important role in lasing behavior. This was also verified in single-shot pumping experiments, in which the minimum pump pulse duration reached 62.5 ms. In the above explanation we rule out the influences of the very short recovery time of the saturable absorber (about 3–5 μs) and the inversion density of the residual populations on the lasing threshold because of the long pump pulse interval. For high pump frequency or short pulse interval, these two factors will further reduce the minimum pulse duration needed for lasing.

3.3 *Pre-pumping technique*

For many applications of Q-switched lasers, it is required that the output of Q-pulse can be controlled or encoded. This means that the laser output not only has the identical frequency to, but also synchronizes with the pump pulse. The programmable Q-pulse output ranging in a large frequency scope is usually realized through programming the external trigger of the LD driver. It is necessary for a laser system to have nearly the same lasing threshold when the pump frequency ranges in a large scale. The aforementioned results of pulse pumping operation show that the self-Q-switched laser output is unstable and uncontrollable. For instance, under 2.68 W pump power and 20 ms pulse duration, one can achieve 10-Hz Q-switched pulses at 10 Hz pump frequency. But at lower pump frequency no laser radiation can be obtained, whereas at higher pump frequency multi-Q-pulses appear with every pump pulse.

In order to obtain stable and programmable Q-switched output, the changes of pumping-energy-induced thermal effect at different pump frequencies should be reduced to a minimum. Pre-pumping technique was proposed, in which the laser crystal was pumped by a LD with a certain base power and a rectangular power modulation of different frequencies. The base pump power must be lower than the power threshold in cw pumping operation. Therefore the pumping energy of the crystal per second, E, can be written as

$$E = \eta_C \times (P_b \times 1 + P_R \times T_R \times f) , \qquad (2)$$

where P_b is the base pump power (W); P_R, T_R and f are the rectangular peak power (W), pulse duration (s) and pump frequency (Hz), respectively. In normal pulse-pump operation ($P_b = 0$), the pumping energy at pump frequency of 1 kHz is 1000 times as large as that at 1 Hz, therefore the lasing threshold changes greatly due to the strong thermal effect of the laser crystal. But in the pre-pumping operation, E changes much less at different pump frequencies than in normal pulse pumping, especially at high base pump power. Moreover the minimum pulse duration needed for lasing can be reduced significantly, which leads to the enlargement of the frequency range of the programmable Q-pulse.

In the experiment, when the base pump power was 2.0 W (close to the power threshold in cw pumping mode) and rectangular peak power was 3.65 W, the minimum pulse duration for lasing was reduced to only 55 μs at different pump frequencies. According to (2), the change of E is very small at different pump frequencies (e.g. E is 1.6 J and 1.76 J at pump frequencies of 1 Hz and 1 kHz, respectively). At this moment much more stable Q-pulse output was achieved with the highest programmable frequency of 16 kHz, much larger than the 2 kHz obtained in normal pulse pumping at the same pump power. At lower base pump power of 1.35 W and 3.0 W rectangular peak power, the minimum pulse duration for lasing was increased to about 400 μs, a very weak frequency-dependent laser threshold with respect to the pump pulse duration was still observed. In all pre-pumping operation the Q-pulse shape and pulse energy of the laser are exactly the same as those in normal cw or pulse-pumping mode.

Although the pre-pumping technique is similar to the well-known gain-switch method, in which single longitudinal mode or Q-pulse is obtained in solid-state lasers [9, 10], in this experiment the purpose of using this technique is to overcome the different thermal effects of the crystal and make the change of the lasing threshold much smaller at different pump frequencies.

4 Conclusion

Pre-pumping technique is proposed to solve the uncontrollable Q-switched pulse resulting from pumping-induced thermal effects of the laser crystal at different pump frequencies in a LD-pumped Cr^{4+}, Nd^{3+} codoped self-Q-switched YAG laser. A stable 1064-nm Q-pulse with 30-ns pulse width (FWHM) and 0.5-μJ pulse energy is obtained. The programmable Q-pulse frequency available is up to 16 kHz, much higher than that obtained in normal pulse pumping. The experimental results show that the characteristic of the Q-switch does not change at all, as compared to normal cw or pulse pumping operation.

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