

> 1 MW peak power, an efficient Yb:YAG/Cr⁴⁺:YAG composite crystal passively Q-switched laser

Jun Dong, Yingying Ren and Huihui Cheng

Department of Electronic Engineering, School of Information Science and Technology, Xiamen University, Xiamen 361005, People's Republic of China

E-mail: jdong@xmu.edu.cn

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Abstract

An efficient Yb:YAG/Cr⁴⁺:YAG composite crystal passively Q-switched laser with a peak power of over 1 MW has been developed under quasi-continuous-wave (QCW) laser-diode pumping. A maximum output energy of 19 mJ was obtained when the available input pump energy was 86 mJ, the corresponding optical-to-optical efficiency was over 22%. A single passively Q-switched laser pulse with a pulse energy of 1.6 mJ and a pulse width of 1.46 ns was achieved. The peak power was 1.08 MW. Near-diffraction-limited beam quality with M^2 of less than 1.75 was achieved in the QCW laser-diode pumped Yb:YAG/Cr⁴⁺:YAG composite crystal passively Q-switched laser.

Keywords: composite crystal, passively Q-switched, Yb:YAG, Cr⁴⁺:YAG, QCW laser-diode pumping

(Some figures may appear in colour only in the online journal)

1. Introduction

Cr⁴⁺:YAG passively Q-switched lasers with high peak power are widely used in laser processing, laser ignition, efficient nonlinear frequency conversion, etc [1, 2]. Composite crystals have been widely used in the construction of compact passively Q-switched lasers since the advent of Cr⁴⁺:YAG passively Q-switched lasers [3]. Yb:YAG crystal is favored because it has a small quantum defect (8.6%) for efficient laser operation, a small emission cross section to obtain high pulse energy, a long lifetime for energy storage [4] and a high doping concentration [5]. A high peak power Yb:YAG/Cr⁴⁺:YAG composite ceramic passively Q-switched microchip laser has been demonstrated with a peak power of 0.72 MW [6]. Yb:YAG/Cr⁴⁺:YAG composite crystal lasers have been demonstrated with external and microchip resonators; however, optical breakdown occurred in the surfaces of the Yb:YAG/Cr⁴⁺:YAG composite crystal for the microchip cavity, and the optical efficiency was less than 5% in the external cavity [7]. Because of the quasi-three-level nature of Yb:YAG crystal,

the thermal effect is a main factor that limits efficient laser performance. Recently, a quasi-continuous-wave (QCW) laser diode operating at low repetition rate has been used to pump Cr⁴⁺:YAG passively Q-switched Yb:YAG lasers for the generation of a high peak power laser pulse because it provides a high pump intensity and alleviates the thermal effect of Yb:YAG crystal. A QCW laser-diode pumped Cr⁴⁺:YAG passively Q-switched Yb:YAG microlaser has been demonstrated with an optical efficiency of 25% [8]; however, the peak power was only 200 kW. A peak power of over 2.8 MW has recently been obtained by decreasing the initial transmission of the Cr⁴⁺:YAG crystal to 89% and decreasing the reflectivity of the output coupler to 50% [9]; however, the optical efficiency was less than 15%. Enhanced performance of a Cr⁴⁺:YAG passively Q-switched Yb:YAG laser with diamond surface cooling has been demonstrated with an optical efficiency of 25% [10]. Efficient performance of an Yb:YAG/Cr⁴⁺:YAG composite crystal pumped with a CW laser diode has been achieved with an optical-to-optical efficiency of 36% with respect to the absorbed pump

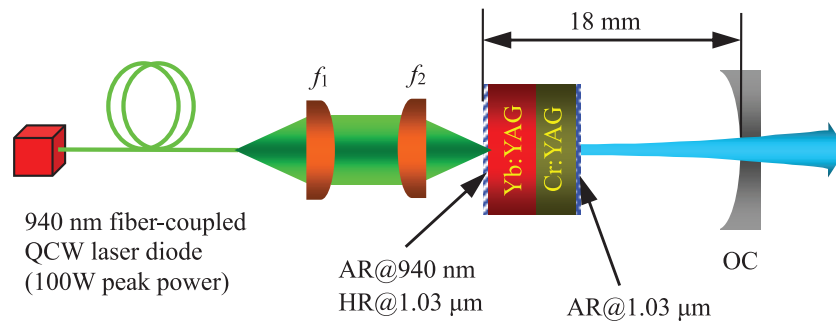


Figure 1. Experimental setup of the QCW laser-diode end-pumped Yb:YAG/Cr⁴⁺:YAG composite crystal passively *Q*-switched laser. f_1 is a focusing lens with 8 mm focal length; f_2 is a focusing lens with 11 mm focal length; OC is the output coupler.

power [11]. An Yb:YAG/Cr⁴⁺:YAG composite crystal passively *Q*-switched microchip laser with an optical efficiency of 41% has been demonstrated under high-brightness single-emitter laser-diode pumping [12]. However, the pulse energy obtained from these lasers was limited by the high initial transmission of the saturable absorber.

In this paper, a highly efficient, high peak power Yb:YAG/Cr⁴⁺:YAG composite crystal passively *Q*-switched laser is developed under QCW laser-diode pumping. The output energy from the Yb:YAG/Cr⁴⁺:YAG composite crystal with 70% initial transmission is 19 mJ at an input pump energy of 86 mJ. A highest optical-to-optical efficiency of over 22% is achieved at the available input pump energy. Laser pulses with a pulse energy of 1.6 mJ, pulse width of 1.46 ns and peak power of over 1.08 MW are obtained.

2. Experiments

The experimental setup of the QCW laser-diode pumped Yb:YAG/Cr⁴⁺:YAG composite crystal passively *Q*-switched laser is shown in figure 1. An Yb:YAG/Cr⁴⁺:YAG composite crystal fabricated with thermal bonding technology was used in the laser experiments. The thicknesses of the Yb:YAG part and Cr⁴⁺:YAG part in the Yb:YAG/Cr⁴⁺:YAG composite crystal were 1.2 mm and 1 mm, respectively; the total thickness of the Yb:YAG/Cr⁴⁺:YAG composite crystal was 2.2 mm. The doping concentration of Yb³⁺ ions was 10 at.% and the initial transmission of the Cr⁴⁺:YAG was 70%. The Yb:YAG surface was coated for anti-reflection (<10%) at 940 nm and high reflection (>99.8%) at 1030 nm to act as the rear cavity mirror of the laser. The anti-reflection coating (<0.25%) at 1030 nm was deposited on the Cr⁴⁺:YAG surface. Based on our previous works on Yb:YAG/Cr⁴⁺:YAG composite crystal passively *Q*-switched lasers [11, 12], a concave cavity mirror with 70 mm curvature and 50% transmission at 1030 nm was chosen as the output coupler to avoid coating damage under high peak power laser operation. The cavity length was set to 18 mm. A fiber-coupled, conductive-cooled, 940 nm QCW laser diode (Dilas laser diode) was used as the pump source. The core diameter of the fiber was 200 μm with a numerical aperture of 0.22. The peak power of the QCW laser diode could reach up to 100 W depending on the driving current. The pump pulse duration was set to 0.9 ms (it could be adjusted from 0.2

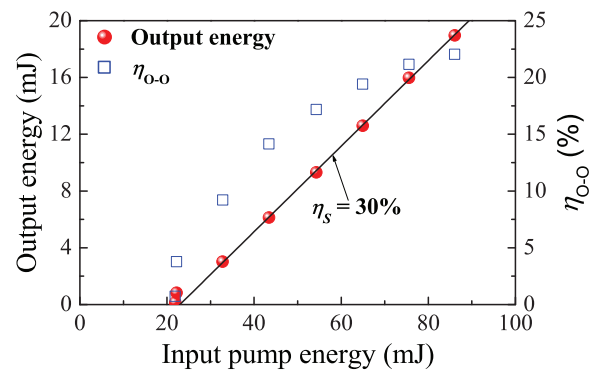


Figure 2. Output energy and optical-to-optical efficiency of the Yb:YAG/Cr⁴⁺:YAG composite crystal passively *Q*-switched laser as a function of the input pump energy. The solid line is a linear fit of the experimental data.

to 10 ms), and the repetition rate was set to 50 Hz (it could also be adjusted from 0.5 Hz up to 2500 Hz) to alleviate the thermal effect of the Yb:YAG/Cr⁴⁺:YAG composite crystal. The pump light from the fiber was collimated and focused with an optical coupling system. The diameter of the focus spot after the optical coupling system was measured to be 180 μm . The laser experiment was carried out at room temperature without an active cooling system. The average output power was measured with a Thorlabs PM200 power meter. The emission spectra of the laser were measured with an Anritsu optical spectral analyzer (MS9740A). The laser pulse characteristics were detected with a 5 GHz InGaAs photodiode and recorded with a 6 GHz bandwidth Tektronix digital phosphor oscilloscope (TDS6604).

3. Results and discussion

The output energy and the optical-to-optical efficiency (η_{o-o}) of the Yb:YAG/Cr⁴⁺:YAG composite crystal passively *Q*-switched laser as a function of the input pump energy are shown in figure 2. The pump energy threshold was 21.5 mJ. The output energy increased linearly with the input pump energy. No saturation of the output energy was observed; therefore, the output energy can be further scaled by increasing the input pump energy. The maximum output energy of 19 mJ was obtained at the available input pump energy of 86 mJ.

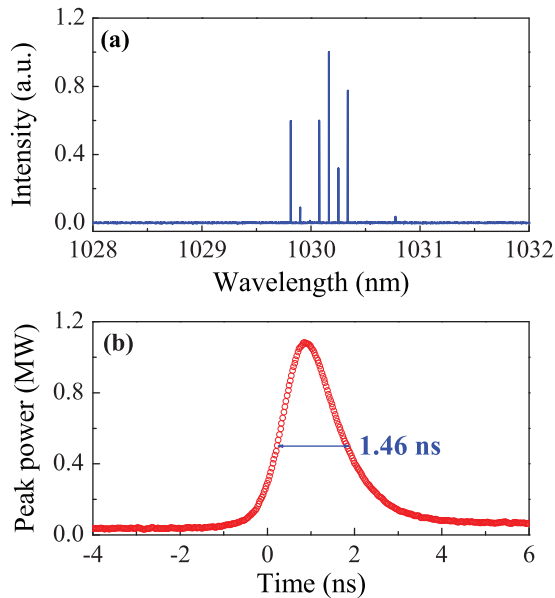


Figure 3. (a) The laser emission spectrum of the Yb:YAG/Cr⁴⁺:YAG composite crystal passively *Q*-switched laser at an input pump energy of 54 mJ. (b) A typical pulse profile of the Yb:YAG/Cr⁴⁺:YAG composite crystal passively *Q*-switched laser with a pulse width of 1.46 ns and a peak power of over 1.08 MW.

The optical-to-optical efficiency increased with the input pump energy and the highest optical-to-optical efficiency of 22% was achieved at the maximum available input pump energy (86 mJ), which was 1.5 times that obtained in an Yb:YAG/Cr⁴⁺:YAG microlaser with a plano-convex cavity under 120 W QCW laser-diode pumping [9]. The highly efficient laser performance of the QCW laser-diode end-pumped Yb:YAG/Cr⁴⁺:YAG composite crystal passively *Q*-switched laser was attributed to the high pump power intensity and good mode overlap between the laser beam and the pump beam. High pump intensity depletes the ground state population of the Yb:YAG crystal and increases the inversion population for efficient laser operation. Depletion of the ground state population alleviates the thermal effect of the Yb:YAG crystal and thus improves the laser performance. The low repetition rate (50 Hz) of the QCW laser diode also alleviates the thermal effect of the Yb:YAG/Cr⁴⁺:YAG composite crystal.

The measured laser emission spectra show that multi-longitudinal-mode oscillation is dominant in the Yb:YAG/Cr⁴⁺:YAG composite crystal passively *Q*-switched laser. The number of longitudinal modes increases with the input pump energy. Figure 3(a) shows a typical laser emission spectrum of the Yb:YAG/Cr⁴⁺:YAG passively *Q*-switched laser at an input pump energy of 54 mJ. Eight longitudinal modes oscillate and the bandwidth of the laser emission spectrum is 0.96 nm. The mode separation between longitudinal modes was measured to be 0.0864 nm. The longitudinal mode separation of the Yb:YAG/Cr⁴⁺:YAG passively *Q*-switched laser is about three times wider than the free spectral range of 0.028 nm for a cavity length of 18 mm. The wide separation of longitudinal modes is attributed to the combination mode selection of the 2.2 mm-thick Yb:YAG/Cr⁴⁺:YAG composite crystal plate and

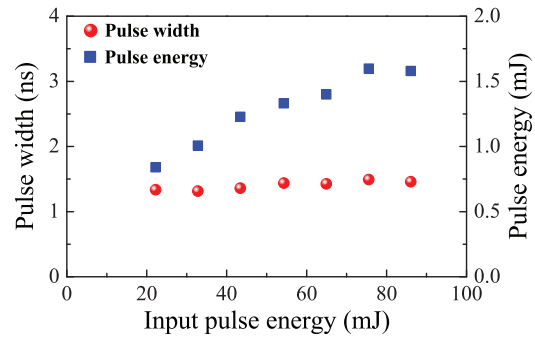


Figure 4. The pulse width and pulse energy of the Yb:YAG/Cr⁴⁺:YAG composite crystal passively *Q*-switched laser as a function of the input pump energy.

the output coupler. On further increasing the input pump energy, the number of longitudinal modes remains almost unchanged; however, the intensities of the individual longitudinal modes vary due to the strong mode competition.

Figure 3(b) shows a typical laser pulse profile of the Yb:YAG/Cr⁴⁺:YAG composite crystal passively *Q*-switched laser at an input pump energy of 86 mJ. A total output energy of 19 mJ was obtained. Twelve *Q*-switched pulses were observed. Therefore, the output passively *Q*-switched laser pulse energy was measured to be 1.6 mJ. The pulse width was measured to be 1.46 ns. The peak power was 1.08 MW.

Figure 4 shows the variation of the pulse width and pulse energy of the Yb:YAG/Cr⁴⁺:YAG composite crystal passively *Q*-switched laser with the input pump energy. Although the pulse width increases slightly from 1.33 to 1.46 ns with the input pump energy, the variation of the pulse width with the input pump energy is less than 10% and the pulse width remains nearly constant with the input pump energy. The broadening of the pulse width with the input pump energy is attributed to the increase of the initial transmission of the Cr⁴⁺:YAG saturable absorber. The temperature of the Cr⁴⁺:YAG crystal in the Yb:YAG/Cr⁴⁺:YAG composite crystal increases with the input pump energy. The initial transmission of the Cr⁴⁺:YAG crystal increases with the temperature [13], while the pulse width is governed by the initial transmission of the Cr⁴⁺:YAG saturable absorber; the higher the initial transmission of the Cr⁴⁺:YAG crystal is, the larger the pulse width is. The *Q*-switched pulse energy increases slowly from 0.84 to 1.6 mJ with the input pump energy until the input pump energy reaches 75 mJ and then remains constant with further increase of the input pump energy. The highest pulse energy of 1.6 mJ was obtained at the maximum available input pump energy of 86 mJ. The pulse energy remains constant when the saturable absorber is fully bleached under a certain input pump energy. The pulse energy could be further scaled by adopting a large pump beam diameter or using low initial transmission of the Cr⁴⁺:YAG crystal.

Figure 5 shows the peak power of the QCW laser-diode pumped Yb:YAG/Cr⁴⁺:YAG composite crystal passively *Q*-switched laser. The peak power increases from 0.64 to 1.08 MW with the input pump energy. The peak power of the Yb:YAG/Cr⁴⁺:YAG composite crystal passively *Q*-switched

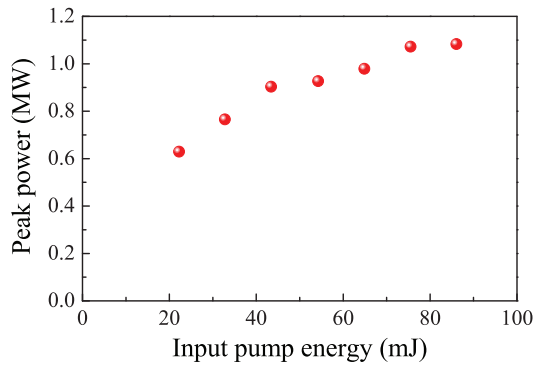


Figure 5. The peak power of the Yb:YAG/Cr⁴⁺:YAG composite crystal passively Q-switched laser as a function of the input pump energy.

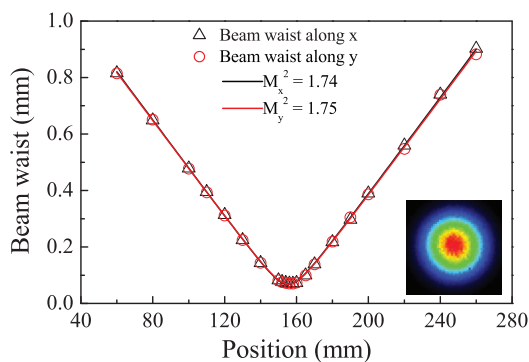


Figure 6. The output laser beam profile and beam quality of the Yb:YAG/Cr⁴⁺:YAG composite crystal passively Q-switched laser.

laser under QCW laser-diode end-pumping could be further scaled by adopting a microchip laser configuration to shorten the pulse width.

The output laser transverse beam profile is shown in the inset in figure 6. The laser beam profile is close to the fundamental transverse electromagnetic mode (TEM₀₀). The transverse laser mode remains the same within the available input pump energy. The measured output beam diameter near the output coupler was 160 μm . The measured beam quality of the QCW laser-diode pumped Yb:YAG/Cr⁴⁺:YAG composite crystal passively Q-switched laser is given in figure 6. Near-diffraction-limited output laser beam quality with M_x^2 of 1.74 and M_y^2 of 1.75 was achieved.

4. Conclusion

A highly efficient, high peak power Yb:YAG/Cr⁴⁺:YAG composite crystal passively Q-switched laser end-pumped by a fiber-coupled QCW laser diode has been demonstrated. An output energy of 19 mJ was achieved at an input pump energy of 86 mJ. An optical-to-optical efficiency of 22% was achieved in the QCW laser-diode pumped Yb:YAG/Cr⁴⁺:YAG composite crystal passively Q-switched laser. Passively Q-switched laser pulses with a pulse width of 1.46 ns and a pulse energy of 1.6 mJ were obtained; a peak power of 1.08 MW was achieved. Meanwhile, near-diffraction-limited

beam quality was achieved in the QCW laser-diode pumped Yb:YAG/Cr⁴⁺:YAG composite crystal passively Q-switched laser.

Acknowledgments

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