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2013 Laser Phys. 23 035802

(http://iopscience.iop.org/1555-6611/23/3/035802)

Laser Phys. **23** (2013) 035802 (5pp) doi:10.1088/1054-660X/23/3/035802

Highly efficient passively Q-switched Yb:YAG microchip lasers under high intensity laser-diode pumping

J Dong, G Y Wang and Y 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

Received 6 December 2012
Accepted for publication 21 December 2012
Published 23 January 2013
Online at stacks.iop.org/LP/23/035802

Abstract

A highly efficient Cr^{4+}:YAG passively Q-switched Yb:YAG microchip laser has been demonstrated at room temperature by high-brightness single-emitter laser-diode pumping. The maximum average output power of 1.53 W was obtained at the absorbed pump power of 3.5 W. The optical-to-optical efficiency was 44% with respect to the absorbed pump power. Laser pulses with a pulse width of 2.9 ns, pulse energy of 11.3 μJ, and peak power of 3.9 kW were obtained. The high pump power intensity from a high-brightness single-emitter laser-diode plays an important role in the alleviation of thermal effects and the efficient performance of Cr^{4+}:YAG passively Q-switched Yb:YAG microchip lasers.

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

1. Introduction

Laser-diode pumped Cr^{4+}:YAG passively Q-switched microchip lasers with short pulse width and high peak power are widely used in remote sensing, range finders, material processing, laser ignition, and so on [1–3]. Yb:YAG crystals were widely used in passively Q-switched microchip lasers because they have some remarkable merits such as a long storage lifetime, a very low quantum defect, broad absorption bandwidth, a smaller emission cross section, and easy growth of high doping concentration crystals. A passively Q-switched Yb:YAG laser with Cr^{4+}:YAG as saturable absorber was first demonstrated by using a Ti:sapphire laser as the pump source [4]. Laser-diode pumped passively Q-switched Yb:YAG/Cr:YAG microchip lasers with sub-nanosecond pulse width and high peak power have been demonstrated [5, 6]. The effects of different Yb:YAG, Cr^{4+}:YAG crystal and ceramic combinations on the performance of passively Q-switched microchip lasers have been investigated and it has been found that the Yb:YAG/Cr^{4+}:YAG crystal combination provides efficient laser performance with an optical-to-optical efficiency of 23% [7]. The efficient passively Q-switched laser performance of the Yb:YAG/Cr^{4+}:YAG crystal combination was attributed to the crystalline orientation selected linear polarization of the Yb:YAG crystal [8] and the nonlinear saturation absorption of the Cr^{4+}:YAG crystal depending on the crystalline orientations in the (111) plane [9]. However, the thermal loading of the Yb:YAG crystal limits the laser efficiency, and the quasi-three-level property of the Yb:YAG crystal causes the population in the lower laser level to increase significantly with rising temperature of the Yb:YAG crystal induced by the pump power. Recently synthetic diamond was used as a heat spreader for the heat management of solid-state lasers owing to its excellent optical and mechanical properties together with its high thermal conductivity. Enhanced performance of a passively Q-switched Yb:YAG microchip laser with diamond cooling has been achieved with optical-to-optical efficiency of 25% compared to 8.3% without a diamond heat spreader [10]. Efficient laser performance of Yb:YAG crystals has been demonstrated at cryogenic temperature [11, 12]. Cooling of Yb:YAG crystals makes Yb:YAG lasers oscillate efficiently, however, lasers become complex by using high thermal conductivity diamond or sapphire as heat spreaders, or using other cryogenic

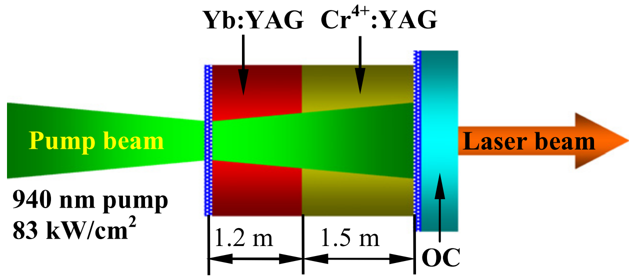

Figure 1. Schematic diagram of the laser-diode pumped Cr^{4+}:YAG passively *Q*-switched Yb:YAG microchip laser with high power intensity laser-diode pumping. OC is the output coupler.

cooling systems. Fortunately, the optical-to-optical efficiency of Yb:YAG crystal is dramatically improved under the high pump power intensity at room temperature [13], and the optical-to-optical efficiency close to the quantum efficiency limit (90%) continuous-wave laser oscillation in Yb:YAG microchip crystal at room temperature has been demonstrated by a high intensity Ti:sapphire laser or tightly focused laser-diode pumping [14, 15]. With the rapid development of high-brightness single-emitter laser-diodes, compact high intensity pump sources are available and make efficient passively *Q*-switched Yb:YAG microchip lasers possible.

In this paper, a highly efficient Cr^{4+}:YAG passively *Q*-switched Yb:YAG microchip laser has been demonstrated at room temperature by high-brightness single-emitter laser-diode pumping. An optical-to-optical efficiency of 44% was achieved, which is the highest efficiency achieved ever in passively *Q*-switched microchip lasers to the best of our knowledge. The effects of the transmission of the output coupler (T_{oc}) and the pump power on the performance of a Cr^{4+}:YAG passively *Q*-switched Yb:YAG microchip laser has been investigated.

2. Experimental setup

The schematic diagram of an efficient Cr^{4+}:YAG passively *Q*-switched Yb:YAG microchip laser with high power intensity laser-diode pumping is shown in figure 1. The Yb:YAG and Cr^{4+}:YAG crystals used in the experiments were grown by the Czochralski (Cz) method along the $\langle 111 \rangle$ direction. A plane-parallel 1.2 mm-thick Yb:YAG crystal plate doped with 10 at.% Yb^{3+} ions was used as the gain medium. One surface of the Yb:YAG crystal was coated with anti-reflection at 940 nm and high reflection at 1030 nm to act as a cavity mirror of the laser. The other surface was coated with anti-reflection at 1030 nm to reduce the intracavity loss. One uncoated 1.5 mm-thick Cr^{4+}:YAG crystal with initial transmission of 95% was used as a *Q*-switch. Several 2 mm-thick BK7 glass plane-parallel mirrors with different transmissions from 30% to 60% at 1030 nm were used as output couplers. A high-brightness 940 nm single-emitter laser-diode with a 1 μm × 50 μm emission cross section was used as the pump source. The divergence angle of the fast-axis was shaped to be 10° with a microlens on the output facet of the laser-diode. Two lenses with 8 mm focal length

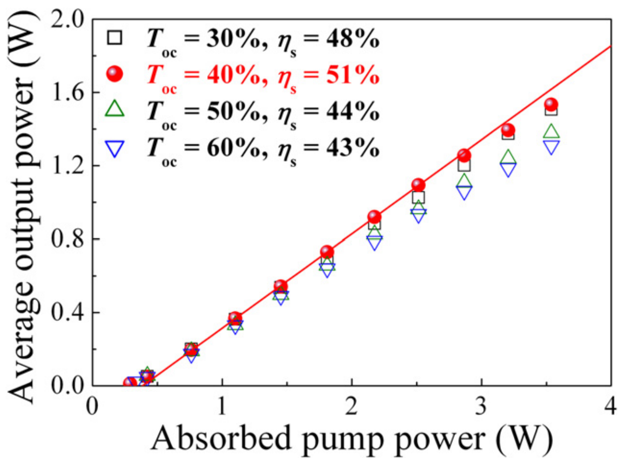

Figure 2. Average output power of Cr^{4+}:YAG passively *Q*-switched Yb:YAG microchip lasers as a function of the absorbed pump power. The solid line shows the linear fit of the experimental data for $T_{oc} = 40\%$.

were used to collimate and focus the pump beam on the Yb:YAG crystal rear surface, and the footprint of the pump beam spot was measured to be 80 × 80 μm^2, and the incident pump power intensity reached up to 83 kW cm^{-2} at the output power of 5.2 W. The Cr^{4+}:YAG passively *Q*-switched Yb:YAG lasers were operated at room temperature without active cooling. The laser emitting spectra were measured with an ANDO (AQ6317B) optical spectral analyzer. The average output power and pulse characteristics were measured with a Thorlabs PM200 power meter and 6 GHz TDS6604 Tektronix digital oscilloscope, respectively.

3. Results and discussion

The average output power of the Cr^{4+}:YAG passively *Q*-switched Yb:YAG microchip lasers as a function of the absorbed pump power for different output couplings (T_{oc}) is shown in figure 2. The absorbed pump power threshold was as low as 0.3 W. The average output power increases nearly linearly with the absorbed pump power for $T_{oc} = 30, 40, 50$, and 60%. The slope efficiencies were 48, 51, 44, and 43% for $T_{oc} = 30, 40, 50$, and 60%, respectively. There is an optimum transmission of the output coupler, $T_{oc} = 40\%$, for the best laser performance of laser-diode pumped Cr^{4+}:YAG passively *Q*-switched Yb:YAG microchip lasers. A maximum average output power of 1.53 W was obtained at the absorbed pump power of 3.5 W for $T_{oc} = 40\%$. The corresponding optical-to-optical efficiency of 44% was achieved, which is the highest optical-to-optical efficiency achieved ever in passively *Q*-switched microchip lasers. The optical-to-optical efficiencies were measured to be 43, 39, and 37% for $T_{oc} =$ 30, 50, and 60%, respectively. There was no saturation of the average output power for different output couplings used in the experiments. This may be attributed to the efficient laser operation of the Yb:YAG crystal and alleviation of thermal effects under high pump power intensity even working at room temperature. Therefore, the average output power of Cr^{4+}:YAG passively *Q*-switched Yb:YAG microchip lasers

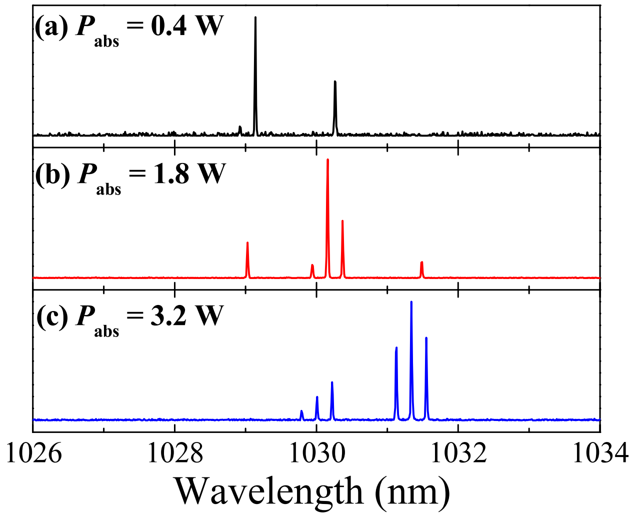

Figure 3. Typical laser emitting spectra of the Yb:YAG/Cr^{4+}:YAG passively Q-switched microchip laser under different pump power levels for $T_{oc} = 40\%$.

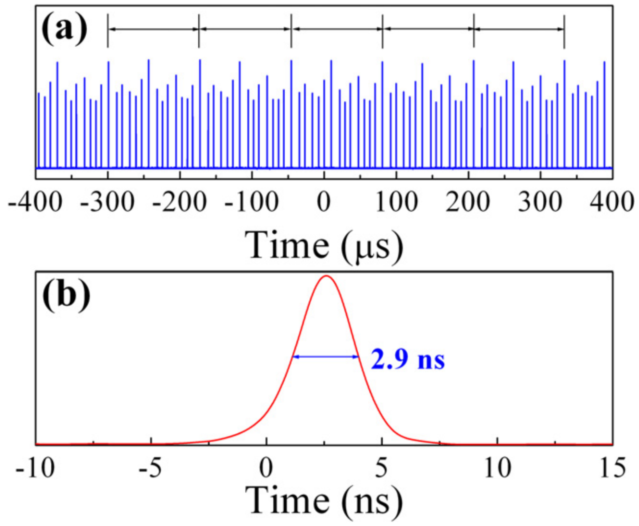

Figure 4. (a) Laser pulse train; (b) laser pulse with pulse width of 2.9 ns, pulse energy of 11.3 μJ, and peak power of 3.9 kW at the absorbed pump power of 2.9 W for $T_{oc} = 40\%$.

under high intensity laser pumping can be further scaled by increasing the pump power. The highly efficient performance of Cr^{4+}:YAG passively Q-switched Yb:YAG microchip lasers was attributed to the high pump power intensity used in the laser experiments. The pump power intensity applied on the Cr^{4+}:YAG passively Q-switched Yb:YAG microchip laser reaches up to about 83 kW cm^{-2} at an incident pump power of 5.2 W. Such high pumping 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 measured laser emitting spectra show that the Cr^{4+}:YAG passively Q-switched Yb:YAG microchip lasers oscillate in multi-longitudinal-mode for different output couplings. Figure 3 shows the laser emitting spectra of Cr^{4+}:YAG passively Q-switched Yb:YAG microchip lasers with $T_{oc} = 40\%$ under different absorbed power levels. The number of longitudinal modes increases with the absorbed pump power. Three longitudinal modes were obtained when the absorbed pump power of 0.4 W was applied. Five longitudinal modes oscillated when the absorbed pump power was 1.8 W. Six longitudinal modes were observed when the absorbed pump power was 3.2 W. The separation between longitudinal modes was measured to be about 0.22, 0.9, and 1.12 nm, respectively, wider than the free spectral range $\Delta\lambda_c = 0.108$ nm in the laser cavity filled with gain medium predicted by $\Delta\lambda_c = \lambda^2/2L_c$, [5] where L_c is the optical cavity length and λ is the laser wavelength. The cause of the wide separation between longitudinal modes is attributed to the combination mode selection from the intracavity tilted etalon effect of the Cr^{4+}:YAG, Yb:YAG thin plates and output coupler mirror. The potential output longitudinal modes were selected by the combined etalon effect of the 1.5 mm-thick Cr^{4+}:YAG, 1.2 mm-thick Yb:YAG thin plate, and the 2 mm-thick BK7 glass mirror as an intracavity etalon [5]. The laser emitting wavelength shifts to longer wavelength with absorbed pump power owing to the temperature dependent emission spectra of the Yb:YAG crystal [16].

The typical pulse train and pulse profile of the Cr^{4+}:YAG passively Q-switched Yb:YAG microchip laser at the absorbed pump power of 2.9 W for $T_{oc} = 40\%$ are shown in figure 4. The laser pulse train exhibited stable periodical pulsation owing to the multi-longitudinal modes oscillation in the Cr^{4+}:YAG passively Q-switched Yb:YAG microchip lasers. Stable laser pulse trains with period-14 pulsation were observed as shown in figure 4(a). The repetition rate was measured to be 110.5 kHz. The longitudinal modes competition for the gain results in the fluctuation of intensities of the laser pulses and time jitters of the laser pulse repetition rate. The laser pulses with pulse energy of 11.3 μJ and pulse width (FWHM) of 2.9 ns were obtained, as shown in figure 4(b). The corresponding peak power of the laser pulse was 3.9 kW. The output laser beam profile is close to the fundamental transverse mode and the laser beam diameter near the output coupler was measured to be 80 μm in diameter.

Figure 5 shows the pulse width, repetition rate, f, pulse energy, and peak power of the Cr^{4+}:YAG passively Q-switched Yb:YAG microchip laser as a function of the absorbed pump power for $T_{oc} = 40\%$. The pulse width (FWHM) decreases with the absorbed pump power. Then the pulse width nearly keeps constant at 3 ns with the absorbed pump power when the absorbed pump power is higher than 1.5 W. The repetition rate increases with the absorbed pump power and the highest repetition rate of 125 kHz was obtained at an absorbed pump power of 3.5 W. However, the increase in the ratio of the repetition rate to the absorbed pump power becomes slower when the absorbed pump power is higher than 2 W. This may be caused by the temperature dependent optical spectra of the Yb:YAG crystal [16]. The absorption of the Yb:YAG crystal centered at 940 nm decreases and the absorption of the Yb:YAG crystal centered at 1030 nm

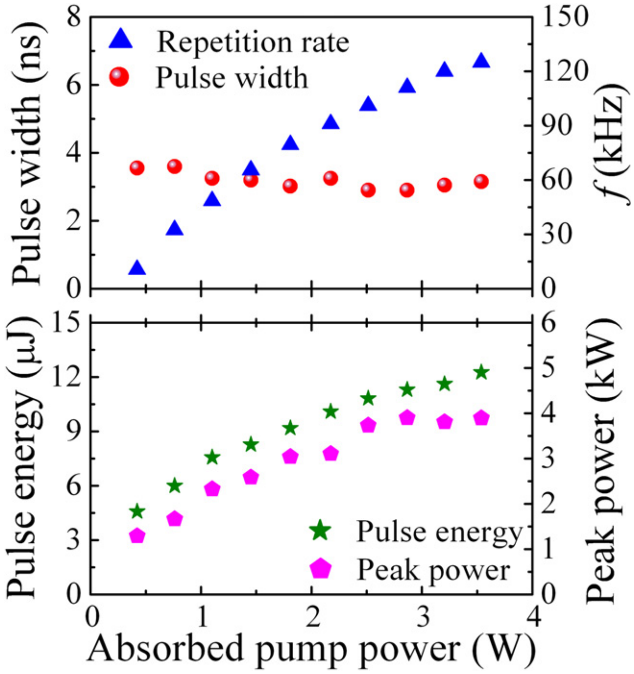

Figure 5. Pulse width, repetition rate, pulse energy and peak power of the Cr^{4+}:YAG passively *Q*-switched Yb:YAG microchip laser as a function of the absorbed pump power for $T_{oc} = 40\%$.

increases with temperature. The pump rate decreases at high pump power owing to the temperature of the Yb:YAG crystal at high pump power. Therefore, the repetition rate increases slowly at high pump power. The pulse energy and peak power increase with the absorbed pump power and tend to increase slowly at high pump power. The pulse width, pulse energy, and peak power are nearly independent of the pump power for different transmissions of output couplers when the absorbed pump power is higher than 2 W. The pulse energy and the pulse width are governed by the initial transmission of the saturable absorber and the parameters of the laser cavity, and do not depend on the pump power, when the pump power is above the pump power threshold, so is the peak power.

The highly efficient Cr^{4+}:YAG passively *Q*-switched Yb:YAG microchip lasers under high pump power intensity pumping open a window for the generation of laser pulses with high efficiency and high peak power. Highly efficient and high peak power Cr^{4+}:YAG passively *Q*-switched Yb:YAG microchip lasers can be constructed by using thin Cr^{4+}:YAG with high Cr doping concentration. Using thin Cr^{4+}:YAG crystal with low initial transmission is also beneficial for short pulse generation.

4. Conclusions

In conclusion, highly efficient Cr^{4+}:YAG passively *Q*-switched Yb:YAG microchip lasers have been demonstrated by high-brightness laser-diode pumping. The best performance of Cr^{4+}:YAG passively *Q*-switched Yb:YAG microchip lasers was achieved with 40% transmission of the output coupler. A maximum output power of 1.53 W was obtained when the absorbed pump power of 3.5 W was applied. The optical-to-optical efficiency of 44% was achieved with respect to the absorbed pump power. Laser pulses with pulse energy of 11.3 μJ, pulse width of 2.9 ns, and peak power of 3.9 kW were achieved. The highly efficient performance of Cr^{4+}:YAG passively *Q*-switched Yb:YAG microchip lasers under high intensity laser-diode pumping provides an effective way for developing efficient passively *Q*-switched quasi-three-level rare-earth doped solid-state lasers at room temperature with high efficiency and high peak power.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No. 61275143), the Program for New Century Excellent Talents in University (Grant No. NCET-09-0669), the Fundamental Research Funds for the Central Universities (Grant No. 2010121058), and the PhD Programs Foundation of the Ministry of Education of China (Grant No. 20100121120019).

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