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Yb:YAG enhanced Cr,Yb:YAG self-Q-switched microchip laser under QCW laser-diode pumping

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ABSTRACT

Enhanced Cr,Yb:YAG self-Q-switched microchip lasers by bonding Yb:YAG crystal have been studied under quasi-continuous-wave (QCW) laser-diode pumping for the first time to our best knowledge. The effects of the pump pulse duration and pump power of the QCW laser-diode on the performance of Yb:YAG/Cr,Yb:YAG microchip lasers have been investigated. The optical efficiency, pulse energy and peak power of the Yb:YAG/Cr,Yb:YAG self-Q-switched laser increase with the pump pulse duration and pump power, and tend to be constant when the pump pulse duration is longer than 1 ms, which is comparable to the fluorescence lifetime of Yb:YAG crystal. Output energy of over 11.7 mJ was obtained at input pump energy of 48.2 mJ; corresponding optical-to-optical efficiency of 24.3% was obtained. Laser pulses with pulse energy of 31 μJ and peak power of 13.3 kW were obtained. The multi-longitudinal modes oscillation around 1030 nm was dominant within the available input pump energy.

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1. Introduction

Self-Q-switched laser crystals, combining the gain medium and saturable absorber in one crystal host, have been demonstrated to be excellent laser materials for compact high peak power solid-state lasers. High optical quality self-Q-switched laser crystals such as Cr,Nd:YAG and Cr,Yb:YAG have been grown by co-doping Cr⁴⁺ ions and Nd³⁺ or Yb³⁺ ions in YAG host crystal. Laser-diode pumped Cr,Nd:YAG and Cr,Yb:YAG self-Q-switched lasers have been demonstrated [1–3]. The broad absorption band, broad emission spectra [4], and high doping concentration [5] make Yb³⁺ ions doped crystals more attractive for developing laser-diode pumped microchip solid state lasers. Laser-diode pumped Cr,Yb:YAG microchip laser with pulse width of 440 ps and peak power of over 53 kW has been demonstrated [6]. However, the fluorescence lifetime of Cr,Yb:YAG self-Q-switched crystal decreases and the defects increase with Cr concentration [7]. The broad absorption spectrum of Cr⁴⁺:YAG from 800 nm to 1300 nm [8,9] results in the strong absorption (about 60% of that around 1 μm) of pump power by Cr⁴⁺ ions at pump wavelength (around 940 nm). The undesirable absorption at 940 nm pump wavelength and the defects of Cr,Yb:YAG crystal degrade the laser performance, therefore, Cr,Yb:YAG self-Q-switched lasers even cannot lase with high Cr concentration [7]. Recently, enhanced Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG crystal or ceramic

have been demonstrated [10,11], the optical efficiency was nearly doubled compared to Cr,Yb:YAG self-Q-switched lasers for the same laser resonator configuration. Enhanced Yb:YAG/Cr,Yb:YAG self-Q-switched microchip lasers have been developed under high brightness single-emitter CW laser-diode pumping [12]. Slope efficiency of 38% and optical-to-optical efficiency of 32% have been obtained with respect to the absorbed pump power. However, the output pulse energy was limited to 12 μJ because the small pump beam area was applied for obtaining high pump power intensity which is beneficial for the efficient performance of Yb:YAG crystal [13]. Because of the quasi-three level nature of Yb:YAG crystal, the self-absorption at lasing wavelength of 1030 nm and the thermal effect of Yb:YAG crystal degrade the laser performance of Yb:YAG crystal. Cryogenically cooling of Yb:YAG crystal improves the laser performance dramatically [13–15]; however, cooling system makes the laser system complex, which is not suitable for developing compact laser systems [14]. Depletion ground state population of Yb:YAG crystal can be realized by applying high pump power intensity. High pump power intensity requires high power concentrated in small area, resulting in severer thermal effect in local area, limiting the output energy of passively Q-switched lasers. Recently, QCW laser-diode working at low repetition rate has been demonstrated to be an alternative way for providing high pump power intensity and alleviating the thermal effect of Yb:YAG crystal. Cr⁴⁺:YAG passively Q-switched Yb:YAG laser has been demonstrated by applying QCW laser-diode pumping [16]; however, the optical efficiency was less than 15% with respect to the input pump energy even when the initial transmission of

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$\text{Cr}^{4+}:\text{YAG}$ was 94%. Low repetition rate QCW laser-diode pumped $\text{Yb}:\text{YAG}/\text{Cr}:\text{Yb}:\text{YAG}$ self-Q-switched microchip lasers will be beneficial for efficient laser operation with high pulse energy.

In this paper, QCW laser-diode end-pumped enhanced $\text{Yb}:\text{YAG}/\text{Cr}:\text{Yb}:\text{YAG}$ self-Q-switched microchip lasers by sandwiching $\text{Cr}:\text{Yb}:\text{YAG}$ crystal between $\text{Yb}:\text{YAG}$ crystal and output coupling mirror has been developed. The effects of pump pulse duration and pump power of QCW laser-diode on the $\text{Yb}:\text{YAG}/\text{Cr}:\text{Yb}:\text{YAG}$ self-Q-switched microchip lasers have been investigated systematically. The optimum pump pulse duration and pump power of QCW laser-diode for achieving highly efficient and high Q-switched pulse energy were obtained. Efficient $\text{Yb}:\text{YAG}/\text{Cr}:\text{Yb}:\text{YAG}$ self-Q-switched microchip laser was achieved. The optical-to-optical efficiency of as high as 24.3% with respect to the input pump energy was achieved. The effects of pulse duration and pump power of the QCW laser-diode on the laser pulse characteristics were addressed.

2. Experiments

The schematic diagram of experimental setup for QCW laser-diode end-pumped $\text{Yb}:\text{YAG}/\text{Cr}:\text{Yb}:\text{YAG}$ self-Q-switched microchip lasers is shown in Fig. 1. The laser head and laser materials used in the experiments are similar to those in Ref. [12]. The difference is that a fiber-coupled QCW laser-diode oscillating at 940 nm is used as pump source. The numerical aperture is 0.22 and the core diameter of the fiber is 200 μm . The output laser from QCW laser-diode is square pulsed laser with pump power amplitude, P_p , pump pulse duration, T_p , and pump repetition rate, $R.R.$ The pump power, P_p , of the QCW laser diode can be reached to 100 W by adjusting the driving current. The pump pulse duration, T_p , varies from 0.2 ms to 10 ms. The Yb^{3+} ions doped laser materials are very sensitive to the working temperature of gain medium. The temperature rise of gain medium increases the population distribution of lower laser level, in the consequence decreases the inversion population, and makes the laser less efficient. The low repetition rate QCW laser-diode as pump source can dramatically alleviate the thermal loading applied on the Yb^{3+} ions doped laser materials by providing sufficient time for releasing the heat generating inside the gain medium and makes laser more efficient. Therefore, the repetition rate, $R.R.$ was set to 50 Hz for effectively alleviating the thermal effect of $\text{Yb}:\text{YAG}/\text{Cr}:\text{Yb}:\text{YAG}$ microchip laser. Two lenses with 8-mm focal length were used to collimate and focus the pump beam on the $\text{Yb}:\text{YAG}$ crystal rear surface, the diameter of the focus spot was measured to be 160 μm . The $\text{Yb}:\text{YAG}/\text{Cr}:\text{Yb}:\text{YAG}$ self-Q-switched microchip lasers operated at room temperature without actively cooling the laser elements. The emitting spectra of the lasers were measured with an Anritsu optical spectral analyzer (MS9740A). The laser pulse characteristics were detected with a 5 GHz InGaAs photo-diode and recorded with a 6 GHz bandwidth Tektronix digital phosphor oscilloscope (TDS6604).

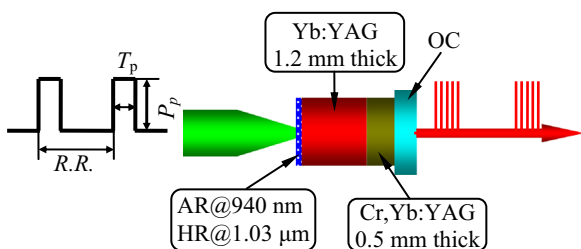


Fig. 1. Schematic diagram of experimental setup for QCW laser-diode end-pumped $\text{Yb}:\text{YAG}/\text{Cr}:\text{Yb}:\text{YAG}$ self-Q-switched microchip laser. OC is the output coupler. T_p is the pump pulse duration, $R.R.$ is the pump repetition rate, P_p is the pump power of QCW laser-diode.

3. Results and discussion

When a square pump pulse with constant amplitude P_p and duration of T_p from a QCW laser-diode is applied on $\text{Yb}:\text{YAG}/\text{Cr}:\text{Yb}:\text{YAG}$ microchip laser, the maximum population lifted to the upper laser level just at the end of the pumping pulse, is then given by [17]

$$N_u(T_p) = \frac{W_p \tau}{W_p \tau + 1} \left[1 - e^{-\frac{T_p(W_p \tau + 1)}{\tau}} \right] n_0 \quad (1)$$

where τ is the lifetime of the upper laser level, n_0 is the total population density of gain medium, W_p is the pump rate, which is proportional to the pump power P_p for the same pump beam area.

The population lifted up to the upper laser level as a function of the pump pulse duration of QCW laser-diode for different pump powers is shown in Fig. 2(a). The population lifted to the upper laser level increases exponentially with the pump pulse duration, T_p , for different pump powers. And the population lifted to the upper laser level tends to be saturated when the pump pulse duration is higher than a certain value depending on the pump power level. The pump pulse duration for achieving saturated population is shortened when the pump power is high, for example, 1 ms for 30 W pump power while 0.75 ms for 50 W pump power. As shown in Fig. 2(b), the population lifted to the upper laser level increases dramatically with the pump power when the pump power is lower than 40 W. The population lifted to the upper laser level increases slowly with further increasing the pump power. The difference of the population lifted to the upper laser level for different pump pulse durations becomes smaller when the pump power is higher than 60 W. When the pump pulse duration of QCW laser-diode is longer than 0.8 ms, the variation of the population lifted to the upper laser level with the pump power is nearly no difference, as shown in Fig. 2(b).

When the pump power of QCW laser-diode was set to 13 W, the output energy, optical-to-optical efficiency, pulse number, pulse width, pulse energy, and peak power of the $\text{Yb}:\text{YAG}/\text{Cr}:\text{Yb}:\text{YAG}$ self-Q-switched microchip laser as a function of the pump pulse duration are shown in Fig. 3. The output energy generated from

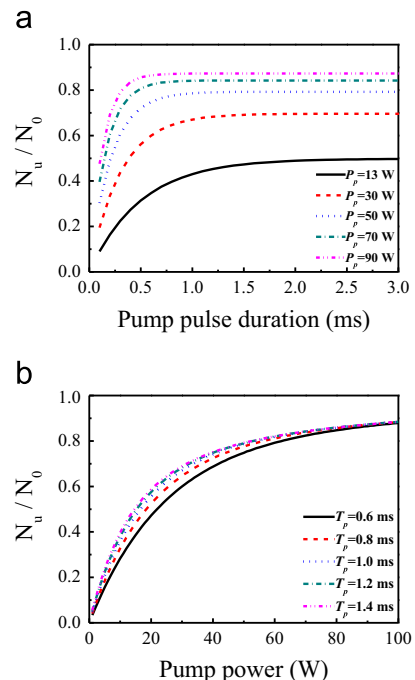


Fig. 2. Population lifted to the upper laser level as a function of (a) pump pulse duration and (b) pump power when a square pump pulse is applied.

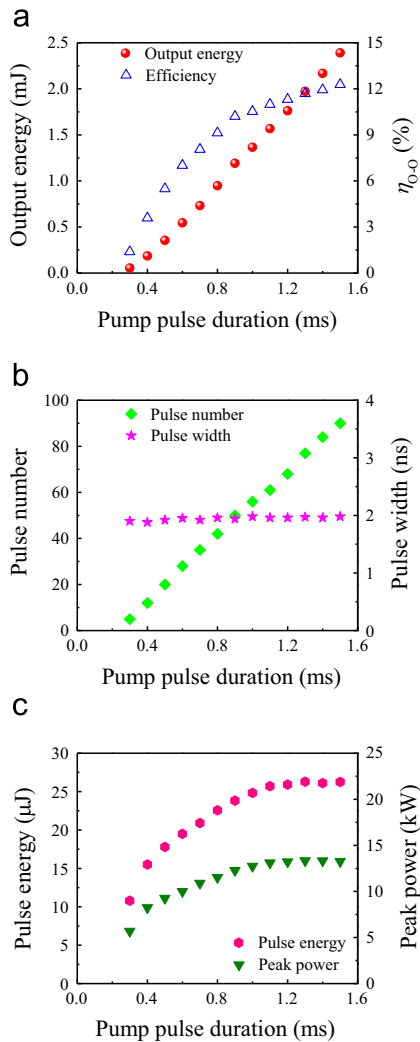


Fig. 3. (a) Output energy, optical efficiency, (b) pulse number, Q-switched pulse width, (c) pulse energy, and peak power of Yb:YAG/Cr,Yb:YAG self-Q-switched microchip lasers as a function of the pump pulse duration, when the pump power and pump repetition rate of the QCW laser-diode were set to 13 W and 50 Hz.

QCW laser-diode pumped Yb:YAG/Cr,Yb:YAG self-Q-switched microchip laser is the total energy from all the pulses generated during pump pulse duration. The optical-to-optical efficiency is the percentage of the output energy to the pump energy. The pulse energy is the energy of each Q-switched pulse generated. The output energy increases near linearly with the pump pulse duration. The optical-to-optical efficiency increases quickly with the pump pulse duration when the pump pulse duration is shorter than 0.8 ms, and then increases slowly with further increasing the pump pulse duration, as shown in Fig. 3(a). The input pump energy is proportional to the pump pulse duration when the pump power of QCW laser-diode is set to a constant. The longer the pump pulse duration is applied, the more the input pump energy is generated. Therefore, the output energy increases with the pump pulse duration. When the pump pulse duration is longer than the lifetime of Yb:YAG crystal (around 1 ms), the population lifted to the upper laser level increases slowly with the pump pulse duration as shown in Fig. 2(a). The contribution to the inversion population for a square pump pulse with pulse duration longer than 1 ms becomes not significant because the fluorescence lifetime of Yb:YAG crystal is around 1 ms. Yb:YAG and Cr,Yb:YAG crystals belonging to quasi-three-level system are very sensitive to the pump intensity for efficient laser operation. When the pump pulse duration is shorter than 0.8 ms, the input pump

energy is not high enough for lifting sufficient population to the upper laser level. Efficient laser performance of Yb:YAG crystal at room temperature needs high pump intensity for depleting the ground state population. Therefore, the input energy increases linearly with the pump pulse duration and the pump power intensity also increases linearly; the optical-to-optical efficiency increases fast with the pump pulse duration when the pump pulse duration is shorter than 0.8 ms. The pump intensity is high enough for lifting most of the population to the upper laser level when the pump pulse duration is longer than 0.8 ms. The intracavity laser intensity is high enough for bleaching Cr⁴⁺ saturable absorber, the pulse energy is fully extracted, and the total pulse energy increases when the pulse number increases with longer pump pulse duration. Thus, the optical-to-optical efficiency of QCW laser-diode pumped Yb:YAG/Cr,Yb:YAG self-Q-switched microchip laser increases slowly with the pump pulse duration when the pump pulse duration is longer than 0.8 ms, exhibiting the same tendency with the population lifted to the upper laser level as a function of the pump pulse duration as shown in Fig. 2(a).

The population lifted to the upper laser level during the pump pulse duration, T_p , will remain in the upper laser level when the T_p is shorter than the fluorescence lifetime of Yb:YAG crystal. When the inversion population is larger than the initial inversion population of Yb:YAG/Cr,Yb:YAG self-Q-switched laser, the self-Q-switched laser pulses are generated. The laser pulse number generated is proportional to the pump pulse duration; the longer the pump pulse duration, the more the laser pulses generated, as shown in Fig. 3(b), while the repetition rate of the Q-switched laser pulses is around 72 kHz. The pump pulse duration of QCW laser-diode has nearly no effect on the Q-switched pulse width, the Q-switched pulse width keeps around 1.9 ns for the different pump pulse durations. The Q-switched laser pulse width is governed by the initial transmission of the saturable absorber, reflectivity of the output coupler and the cavity length according to the theory of passively Q-switched solid state lasers [18], therefore, the pulse width is kept constant when these parameters are set. When the pump power of QCW laser-diode was kept constant, the pump pulse duration determined the inversion population generated in the Yb:YAG and Cr,Yb:YAG crystals, while the pulse width is governed by the photons propagating inside the cavity, therefore, the pump pulse duration has no effect on the Q-switched pulse width.

As shown in Fig. 3(c), the Q-switched pulse energy increases with the pump pulse duration and tends to be saturated when the pump pulse duration of QCW laser-diode is longer than 1 ms. The intracavity laser intensity generated with the input pump energy achieved under a pump pulse with pulse duration shorter than 1 ms is not sufficient to bleach the Cr⁴⁺ saturable absorber, therefore, the Q-switched pulse energy is low. The Cr⁴⁺ saturable absorber is fully bleached when the pump pulse duration is longer than 1 ms, thus, the Q-switched pulse energy is kept unchanged with further increasing the pump pulse duration. The inversion population accumulated in the upper laser state increases with the pump pulse duration when the pump pulse duration is shorter than the radiative lifetime of Yb:YAG crystal. The saturation of the Q-switched pulse energy is caused by the most of the pump energy absorbed in the first period of constant pump duration dispersing before oscillation at low pump power. Owing to the pulse width is not changed with the pump pulse duration, therefore, the variation of the peak power with the pump pulse duration exhibits the same tendency as that for the Q-switched pulse energy.

Besides the pump beam volume, the pump power of QCW laser-diode is the main factor to determine the pump rate applied on the Yb:YAG/Cr,Yb:YAG self-Q-switched microchip lasers. The pump rate is proportional to the pump power of QCW laser-diode.

When the QCW laser-diode is operated at the pump pulse duration of 0.8 ms and the repetition rate of 50 Hz, the output energy, optical-to-optical efficiency, Q-switched pulse number, Q-switched pulse width, pulse energy, and peak power of Yb:YAG/Cr,Yb:YAG self-Q-switched microchip lasers as a function of the pump power of QCW laser-diode are shown in Fig. 4. The output energy increased linearly with the pump power of QCW laser-diode. No output energy saturation was observed, therefore, the output energy can be further scaled by applying high pump power. The maximum output energy of 11.7 mJ was obtained at the applied pump power of 60 W. The corresponding optical-to-optical efficiency of 24.3% was achieved with respect to the input pump energy of 48.2 mJ (pump power is 60 W and pump pulse duration is 0.8 ms), which is about 1.6 times of that in QCW laser-diode pumped plano-convex cavity Yb:YAG/Cr⁴⁺:YAG passively Q-switched micro-laser [16]. The pump energy absorption efficiency of 1.7 mm thick Yb:YAG/Cr,Yb:YAG crystal was measured to be 70%, the absorbed pump energy is 33.7 mJ at the input pump energy of 48.2 mJ. Therefore, the optical-to-optical efficiency of 35% was achieved with respect to the absorbed pump energy, which is even higher than that pumped with high-brightness single-emitter CW laser-diode [12]. The performance of Yb:YAG/Cr,Yb:YAG self-Q-switched microchip laser is dramatically improved by applying QCW laser-diode pumping because the thermal effect

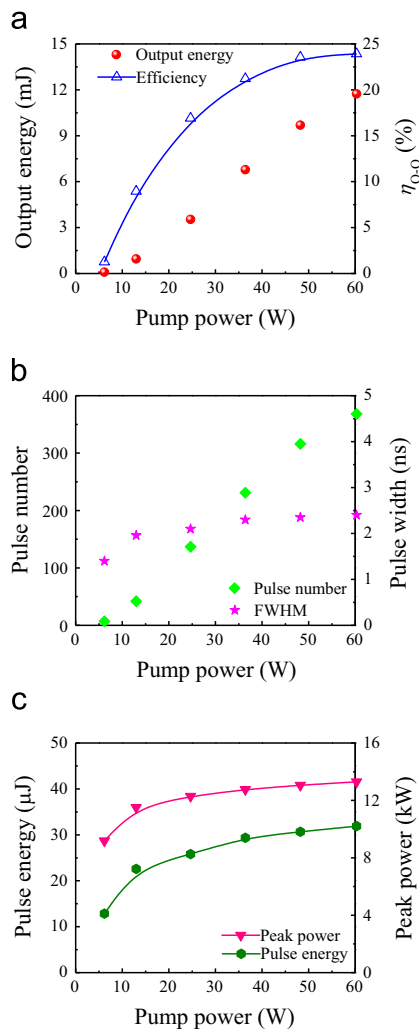


Fig. 4. (a) Output energy, optical efficiency, (b) pulse number, Q-switched pulse width, (c) pulse energy, and peak power of Yb:YAG/Cr,Yb:YAG microchip lasers as a function of the pump power, when the pump repetition rate and pump pulse duration of the QCW laser-diode were set to 50 Hz and 0.8 ms.

of Yb:YAG/Cr,Yb:YAG gain media is effectively alleviated. The optical-to-optical efficiency increases with the pump power of QCW laser-diode and the optical-to-optical efficiency is saturated at the pump power of 60 W, which is coincident with the saturated population achieved at the upper laser level when the QCW laser-diode operates at the pump power of 60 W and the pump pulse duration of 0.8 ms, as shown in Fig. 2(b).

The Q-switched pulse number increases with the pump power of the QCW laser-diode, therefore, the repetition rate of the Q-switched laser pulses increase with the pump power. The Q-switched pulse width increases with the pump power of QCW laser-diode when the pump power is lower than 25 W, and then increases slowly with further increase of the pump power. The broadening of the Q-switched pulse width may be caused by the increasing of the initial transmission of Cr,Yb:YAG crystal under high pump power for long pump pulse duration. The initial transmission of the saturable absorber is the main factor when the reflectivity of the output coupler and the cavity length are set. The higher the initial transmission of the saturable absorber, the wider the pulse width. The higher the pump power applied on the Yb:YAG and Cr,Yb:YAG crystals, the higher the input pump energy generated. Therefore, the local temperature of gain medium rises at high pump power. The initial transmission of Cr,Yb:YAG crystal increases with the pump power, thus, the pulse width is broadened with the pump power. The Q-switched pulse energy increases rapidly with the pump power when the pump power is lower than 25 W. When the pump power is higher than 25 W, the pulse energy tends to increase slowly with the pump power. The maximum pulse energy of 31 μ J was achieved at the pump power of 60 W, which was about two times of that obtained under CW single-emitter laser-diode pumping [12]. The variation of the pulse energy with the pump power is attributed to increase the effective pump power intensity with the pump power of QCW laser-diode when the pump pulse duration is set to constant. The laser mode increases slightly when the high pump power is applied. The peak power of Yb:YAG/Cr,Yb:YAG self-Q-switched microchip lasers was governed by the laser pulse energy and pulse width. The variation of the Q-switched laser peak power keeps the same tendency as that of Q-switched laser pulse energy, as shown in Fig. 4(c). The maximum peak power of 13.3 kW was achieved at the pump power of 60 W.

Fig. 5(a) shows a typical pulse profile of QCW laser-diode pumped Yb:YAG/Cr,Yb:YAG self-Q-switched microchip laser. The symmetrical pulse profile was observed. The pulse width of 1.9 ns and pulse energy of 23 μ J was obtained under pump condition of 50 Hz, 0.8 ms pulse duration and pump power of 13 W, and the

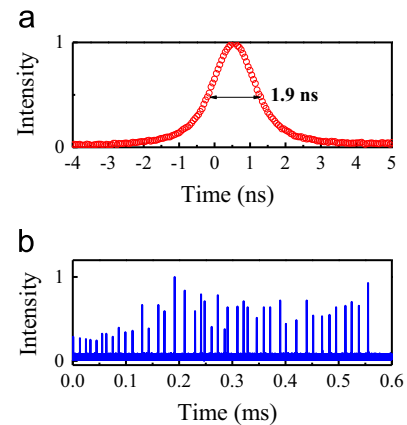


Fig. 5. (a) Pulse profile and (b) pulse trains of QCW laser-diode pumped Yb:YAG/Cr,Yb:YAG self-Q-switched microchip lasers under the pump repetition rate of 50 Hz, pump pulse duration of 0.8 ms and pump power of 13 W.

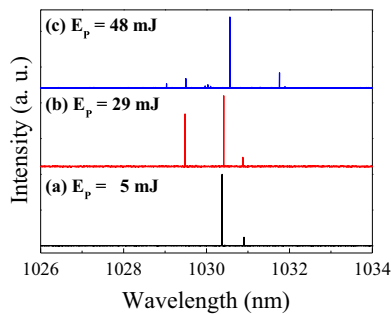


Fig. 6. Laser emitting spectra of QCW laser-diode pumped Yb:YAG/Cr,Yb:YAG self-Q-switched microchip lasers at different input pump energies of (a) 5 mJ, (b) 29 mJ, and (c) 48 mJ.

corresponding peak power of 12 kW was achieved. Fig. 5(b) shows the laser pulse train at the pump power of 13 W and pump pulse duration of 0.8 ms. The fluctuation of the laser pulse intensity was observed. The time jitter and peak-to-peak intensity fluctuation of laser pulses were calculated to be 23% and 32% respectively. The unstable laser pulses were caused by the pump power fluctuation from QCW laser-diode. The stable laser operation can be achieved by apply highly stable QCW laser-diode pumping.

Fig. 6 shows some typical laser emitting spectra of QCW laser-diode pumped Yb:YAG/Cr,Yb:YAG self-Q-switched microchip lasers at different input pump energies. The QCW laser-diode worked at the repetition rate of 50 Hz and the pump pulse width was kept at 0.8 ms. The multi-longitudinal modes oscillation was observed. The laser oscillated at two longitudinal modes when the input pump energy was kept below 10 mJ, as shown in Fig. 6(a). The laser oscillated at three longitudinal modes when the input pump energy was in the range from 10 mJ to 40 mJ. A typical laser emitting spectrum of three longitudinal mode oscillations at the input pump energy of 29 mJ is shown in Fig. 6(b). The number of the longitudinal modes increases with input pump energy when the input pump energy is higher than 40 mJ. A typical laser emitting spectrum of seven longitudinal modes oscillation is shown in Fig. 6(c). The wide separation of longitudinal modes was attributed to the intracavity etalon effect of Yb:YAG and Cr,Yb:YAG thin plates. The central wavelength of laser emitting spectra under different input pump energies nearly kept around 1030.5 nm, which was different from those observed in the CW laser-diode pumped Yb:YAG/Cr,Yb:YAG self-Q-switched lasers [12]. The input pump energy independence of the laser emitting spectra shows that the thermal effect of Yb:YAG/Cr,Yb:YAG self-Q-switched microchip lasers is dramatically alleviated with QCW laser-diode pumping, which is beneficial for the efficient laser performance of Cr⁴⁺:YAG passively Q-switched Yb:YAG solid-state lasers.

4. Conclusions

QCW laser-diode pumped Yb:YAG/Cr,Yb:YAG self-Q-switched microchip lasers enhanced by bonding Yb:YAG crystal have been

developed for the first time to our best knowledge. The effects of the pump pulse duration and pump power of QCW laser-diode on the performance of Yb:YAG/Cr,Yb:YAG self-Q-switched microchip lasers have been investigated systematically. The pump pulse duration and the pump power of QCW laser-diode have great effect on the population lifted to the upper laser level, which mainly determine the laser characteristics of Yb:YAG/Cr,Yb:YAG self-Q-switched microchip lasers. The output energy and optical-to-optical efficiency increase with the pump pulse duration and the pump power of QCW laser-diode. And there are values of pump pulse duration and pump power of QCW laser-diode for achieving saturated pulse energy and optical efficiency. The maximum optical-to-optical efficiency of 24.3% was achieved when the input pump energy of 48 mJ was applied. The Q-switched laser pulses with pulse energy of 31 μ J and peak power of 13.3 kW were obtained. The QCW laser-diode pumping alleviates the thermal effect of Yb:YAG/Cr,Yb:YAG self-Q-switched microchip lasers which is beneficial for developing high peak power passively Q-switched Yb:YAG microchip lasers for various applications.

Acknowledgments

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