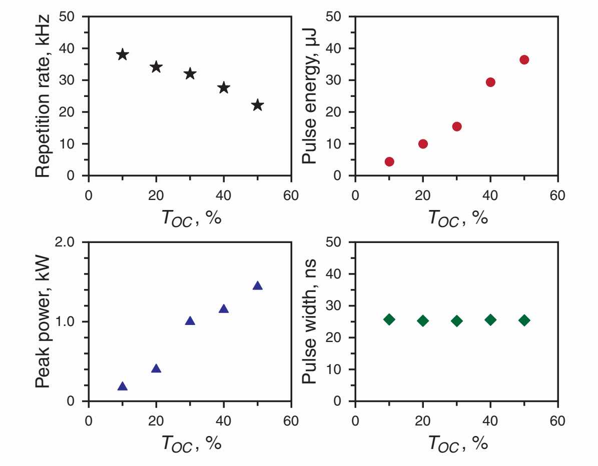
Abstract: Efficient laser-diode pumped self-Q-switched Cr,Yb:YAG lasers by bonding Yb:YAG crystal to increase pump power absorption efficiency have been demonstrated for the first time to our best knowledge. The effect of transmission of output coupler (T_{OC}) on the laser performance has been investigated and found that the best laser performance was achieved with $T_{OC} = 50\%$. Average output power of 1 W was obtained with $T_{OC} = 50\%$ at absorbed pump power of 5.4 W; corresponding optical-to-optical efficiency of 18.5% was obtained with respect to the absorbed pump power. Slope efficiency of 25% was measured with $T_{OC} = 50\%$. Laser pulses with pulse width of 26 ns, pulse energy of 37 μJ, and corresponding peak power of 1.4 kW with $T_{OC} = 50\%$ were obtained. The lasers oscillate in multi-longitudinal-mode; number of the modes increases from two to five with pump power, owing to the mode selection by Cr,Yb:YAG thin plate acting as an intracavity etalon.



Pulse characteristics such as pulse repetition rate, pulse energy, peak power, and pulse width of Yb:YAG/Cr,Yb:YAG self-Q-switched lasers as a function of transmission of output coupler

Efficient, nanosecond self-Q-switched Cr,Yb:YAG lasers by bonding Yb:YAG crystal

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1. Introduction

Diode laser pumped passively Q-switched solid-state lasers are compact and robust lasers with high pulse energies and peak powers in a diffraction-limited output beam, and have many applications such as remote sensing, range finders, pollution detection, lidar, material processing, medical systems, laser ignition, and so on [1–3]. The passively Q-switched lasers are usually operated using a thin gain medium bonded with saturable absorber such as a semiconductor saturable-absorber mirror (SESAM) [4] and bulk "Cr^{4+}" doped crystals [5,6], or Cr:YAG films deposited on the gain medium by molecular beam epitaxy (MBE) [7]. Compared with SESAM or the saturable absorber film deposited on the surface of the gain medium, "Cr^{4+}" doped bulk crystals as saturable absorber have several advantages: high damage threshold, low cost, and simplicity.

The other advantage of "Cr^{4+}" doped bulk crystals is that self-Q-switched laser materials can be fabricated by codoping "Cr^{4+}" ions and lasants in YAG. Cr,Nd:YAG and Cr,Yb:YAG self-Q-switched lasers have been demonstrated [8–10]. The low concentration of Nd^{3+}

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ions in Cr,Nd:YAG crystal limits the laser operation. Efficient laser operation requires absorbing sufficient pump power with short crystal length; a high concentration microchip laser material is required to realize subnanosecond laser operation. Compared with Nd:YAG laser material, Yb:YAG crystal has several advantages such as a long storage lifetime (951 μs) [11], a very low quantum defect (8.6% with pump wavelength of 941 nm and laser wavelength of 1030 nm), resulting in three times less heat generation during lasing than comparable Nd-based laser systems [12], broad absorption bandwidth and less sensitive to diode wavelength specifications [13], a relatively large emission cross section [14] suitable for Q-switching operation, and easy growth of high quality and moderate concentration crystal without concentration quenching [15]. Temperature dependent emission cross section of Yb:YAG materials[14] provides another flexible design for efficient operation of cryogenically-cooled Yb:YAG lasers [16]. Highly efficient intracavity frequency-doubled Yb:YAG lasers have been demonstrated recently [17–20]. Frequency doubling of Yb:YAG lasers at 515 nm matches the highest power line of Ar-ion lasers, thereby leading to the possibility of an all solid-state replacement [21].

In the past decade, high quality transparent Yb:YAG ceramics have been fabricated and efficient laser operation has been demonstrated [22]. Comparative investigation of laser performance of Yb:YAG ceramics and crystals has been done and results show that Yb:YAG ceramics provide comparable or better laser performance comparing to their counterpart Yb:YAG crystals doped with different Yb concentrations [23]. Efficient laser performance of heavy doped Yb:YAG ceramics has been demonstrated recently [24,25]. High power laser-diode pumped Yb:YAG lasers based on Yb:YAG ceramics and crystals have been demonstrated with different laser resonator configuration such as thin disk lasers [26-29], rod lasers [30], microchip lasers [22,31], and slab lasers [32]. Yb:YAG ceramics have been successfully used to generate very-high order Laguerre-Gaussian modes by using a simple short-focus plano-convex glass lens [33] and circular modes by using a spherical intracavity lens [34]. Passively Q-switched Yb:YAG laser with Cr:YAG as saturable absorber was first demonstrated by using Ti:Sapphire laser as pump source [5]. Actively Q-switched Yb:YAG lasers have been demonstrated recently with electro-optical and acoustic-optical modulators [35,36] and show that Yb:YAG is an attractive laser material for laser-diode pumped all solid-state Q-switched lasers, especially for high energy application. Passively Q-switched Yb:YAG microchip laser with 530 ps pulse width has been obtained by using SESAM [4]. Chromium and ytterbium co-doped YAG (Cr,Yb:YAG) crystals have been grown successfully and optical properties of these self-Q-switched laser material have been investigated [37,38]. The self-Q-switched Cr,Yb:YAG laser was first demonstrated using a Ti:Sapphire laser as pump source [10]. The laser-diode pumped self-Q-switched laser pulse output with pulse width of 0.5 ns was achieved with 750-μm-thick Cr,Yb:YAG crystal [39], but the average output power was very low and coating of the crystal was damaged very quickly, so this laser can not be used in practice. Recently, laser-diode pumped Cr,Yb:YAG microchip laser with pulse width of 440 ps, peak power over 53 kW has been demonstrated [40], however, owing to co-doping of chromium ions with Yb into YAG host, the fluorescence lifetime decreases [38] with increase of Cr concentration and there is strong absorption (about 60% of that around 1 μm) of pump power by "Cr^{4+}" ions at pump wavelength (around 940 nm) owing to the broad absorption spectrum of Cr:YAG from 800 to 1300 nm [41,42]. The absorbed pump power threshold is high due to the high intracavity loss induced by the defects introducing Cr ions into Yb:YAG crystal for compact Cr,Yb:YAG microchip laser. The undesirable absorption at pump wavelength of 940 nm for Cr,Yb:YAG self-Q-switched laser crystal limits the laser performance or even can not lase with high Cr concentration [38].

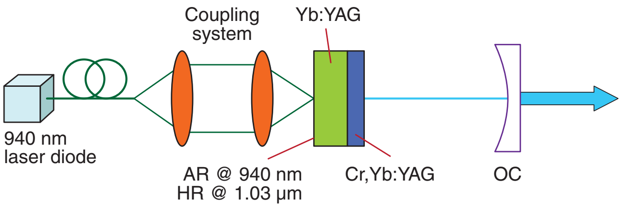

Figure 1 (online color at www.lphys.org) Schematic diagram of experimental setup for laser-diode pumped Yb:YAG/Cr,Yb:YAG self-Q-switched laser. OC is the output coupler

In this paper, enhancement of Cr,Yb:YAG self-Q-switched laser performance was conducted by bonding a Yb:YAG crystal to a self-Q-switched Cr,Yb:YAG crystal. The pump power is absorbed by Yb:YAG crystal; residual pump power after Yb:YAG crystal is further absorbed by Cr,Yb:YAG self-Q-switched crystal to increase the absorption efficiency. The laser performance of laser-diode end-pumped Cr,Yb:YAG self-Q-switched lasers enhanced by bonding Yb:YAG crystal was investigated by varying the transmission of output coupler (T_{OC}). Efficient, high repetition rate, nanosecond pulse width Cr,Yb:YAG self-Q-switched lasers enhanced by bonding Yb:YAG crystal have been demonstrated for the first time to our best knowledge. The enhancement of laser performance of Yb:YAG/Cr,Yb:YAG self-Q-switched lasers were attributed to the increase of inversion population density with bonding Yb:YAG and Cr,Yb:YAG together.

2. Experimental setup

The schematic diagram of experimental setup for enhancement of Cr,Yb:YAG self-Q-switched lasers by bonding Yb:YAG crystal is shown in Fig. 1. A plane-parallel 1-mm-thick Yb:YAG crystal plate doped with 10 at.% Yb^{3+} ions was used as gain medium to absorb main portion of

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the pump power. One surface of the Yb:YAG crystal was coated with anti-reflection at 940 nm and highly 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. An uncoated 0.5-mm thick Cr,Yb:YAG crystal doped with 0.025 at.% "Cr^{4+}" and 10 at.% Yb^{3+} ions was attached together to Yb:YAG crystal to conduct self-Q-switched laser oscillation and further absorb residual pump power for enhancing laser performance. The initial transmission of Cr,Yb:YAG crystal was estimated to be 94% by measuring the absorption spectrum of Cr,Yb:YAG around 1 μm. The mechanically bonded Yb:YAG crystal and Cr,Yb:YAG crystal were held between two copper blocks. Six concave mirrors with 70-mm curvature and different transmissions (T_{OC}) of 5, 10, 20, 30, 40, and 50% at 1030 nm were used as output couplers. The cavity length is 70 mm. A fiber-coupled 940 nm laser diode with core diameter of 200 μm and numerical aperture of 0.22 was used as the pump source. Two lenses with 8-mm focal length were used to focus the pump beam on the Yb:YAG crystal rear surface, the diameter of the pump beam spot was measured to be 160 μm. The Cr,Yb:YAG self-Q-switched lasers enhanced by bonding Yb:YAG crystal operated at room temperature without active cooling. The laser emitting spectra were measured with ANDO (AQ6317B) optical spectral analyzer. Average output power and pulse characteristics were measured with a 3M power meter and 400 MHz Tektronix digital oscilloscope, respectively.

3. Experimental results and discussion

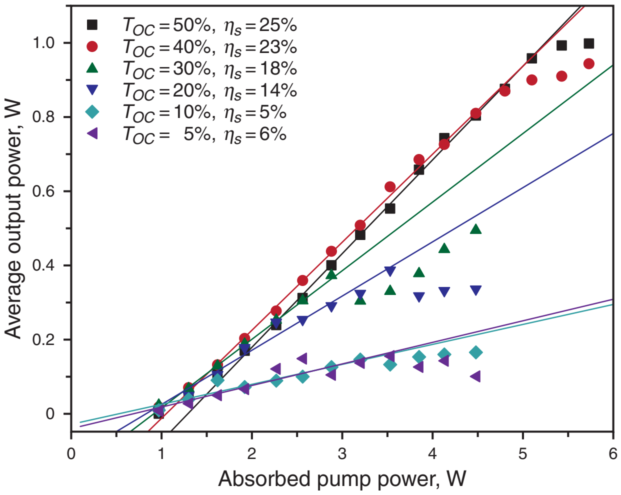

Figure 2 (online color at www.lphys.org) Average output power of Yb:YAG/Cr,Yb:YAG self-Q-switched lasers as a function of the absorbed pump power for different transmission of output coupler, T_{OC}. The lines show the linearly fitting of experimental data for different transmission of output couplers

The average output power of self-Q-switched Yb:YAG/Cr,Yb:YAG lasers as a function of the absorbed pump power for different output couplings (T_{OC}) is shown in Fig. 2. The absorbed pump thresholds are quite similar (about 0.97 W) for different output couplings. The average output power increases nearly linearly with the absorbed pump power when the absorbed pump power is well above the pump power threshold for T_{OC} = 30, 40, and 50%. However, the average output power increases linearly with absorbed pump power at low pump power levels and tends to increase slowly when the absorbed pump power is higher than 3 W for T_{OC} = 5, 10, and 20%. The average output power increases with the transmission of output couplers under the same pump power level. The average output power of passively Q-switched lasers is governed by the pulse energy and pulse repetition rate. The pulse energy of passively Q-switched lasers is proportional to $\ln(1/(1-T_{OC}))$, and increases with transmission of output couplers. Therefore, average output power increases with transmission of output couplers. The slope efficiencies were measured to be about 6, 5, 14, 18, 23, and 25% for T_{OC} = 5, 10, 20, 30, 40, and 50%, respectively. The performance of Yb:YAG/Cr,Yb:YAG self-Q-switched lasers with T_{OC} = 40% and T_{OC} = 50% are comparable. Maximum average output power of 1 W was achieved at absorbed pump power of 5.4 W with T_{OC} = 50%, corresponding optical-to-optical efficiency of 18.5%. Meanwhile, for T_{OC} = 40%, maximum average output power of 0.95 W was achieved at absorbed pump power of 5.4 W, corresponding optical-to-optical efficiency of 18%. The output power tends to be saturated with further increase of pump power owing to the thermal effect of Yb:YAG crystal under high pump power. Laser performance of Yb:YAG/Cr,Yb:YAG self-Q-switched lasers is better than that obtained in laser-diode pumped monolithic Cr,Yb:YAG self-Q-switched lasers with the same plano-concave cavity [43]. For current Yb:YAG/Cr,Yb:YAG self- Q-switched laser, the inversion population provided with pump power can be expressed according to the exponential absorption law as follows,

$$N_{cw} = \frac{P_p\left[1-\exp(-\alpha_{\mathrm{Yb}} l)\right]}{h\nu_p \pi w_p^2 l}\,\tau + \\ + \frac{P_p \exp(-\alpha l)\left[1-\exp(-\alpha_{\mathrm{CrYb}} l_s)\right]}{h\nu_p \pi w_p^2 l_s}\,\tau_s\,, \tag{1}$$

where P_p is the incident pump power on the laser crystal, α_{Yb} and α_{CrYb} are the absorption coefficients at 940 nm of Yb:YAG crystal and Cr,Yb:YAG crystal; l and l_s are the length of Yb:YAG crystal and Cr,Yb:YAG crystal; τ and τ_s are the luminescence lifetime of Yb:YAG crystal and Cr,Yb:YAG crystal, $h\nu_p$ is the pump photon energy, and w_p is the pump beam waist.

The absorption coefficient of Yb^{3+} ions at peak absorption wavelength of 940 nm is nearly the same

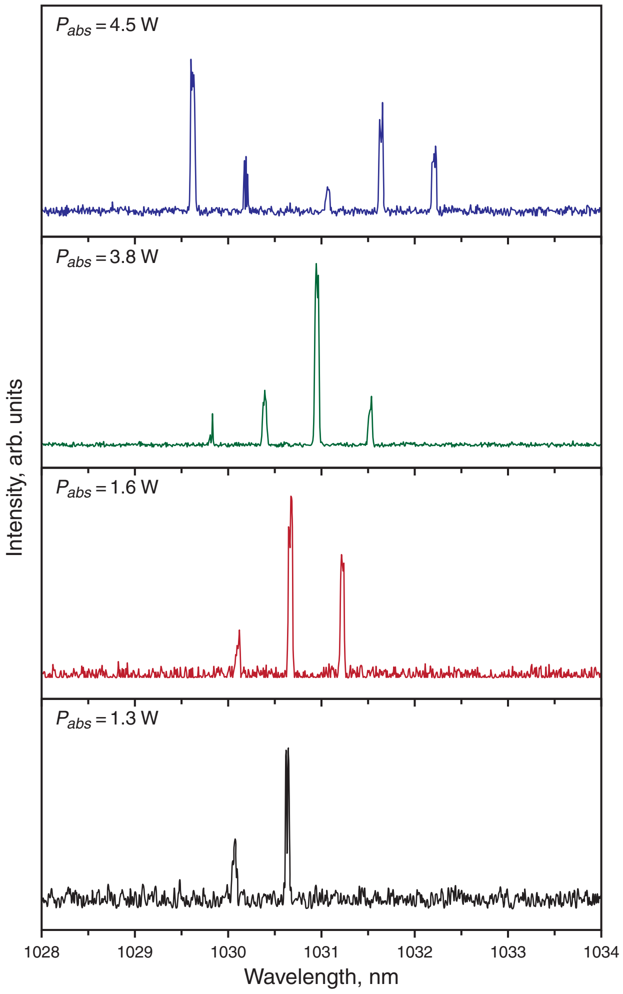

Figure 3 (online color at www.lphys.org) Typical laser emitting spectra of Yb:YAG/Cr,Yb:YAG self-Q-switched laser under different pump power levels for transmission of output coupler, $T_{OC} = 50\%$

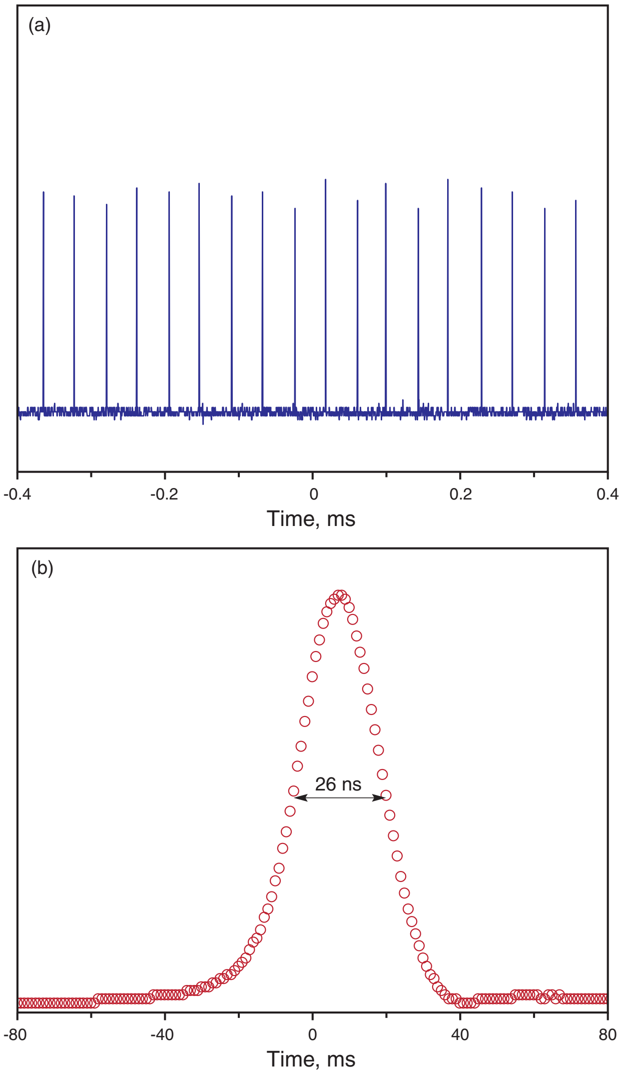

Figure 4 (online color at www.lphys.org) (a) – oscilloscope trace of pulse trains and (b) – laser pulse with 26 ns pulse width and pulse energy of 37 μJ, corresponding to peak power of 1.4 kW

for Yb:YAG crystal doped with 10 at.% Yb ions and Cr,Yb:YAG crystal doped with 10 at.% Yb ions. However, the lifetime of Yb:YAG is about 951 μs and the fluorescence lifetime of Cr,Yb:YAG is about 584 μs [38]. Therefore, the inversion population of 1-mm-thick Yb:YAG crystal is about 1.6 time of that of 1-mm-thick Cr,Yb:YAG crystal by using the first part of Eq. (1). The absorption of pump power is further enhanced by Cr,Yb:YAG crystal, the inversion population achieved by 1-mm-thick Yb:YAG plus 0.5-mm-thick Cr,Yb:YAG combination is about 2 times higher than that of 1-mm-thick Cr,Yb:YAG crystal. Therefore, high efficiency of Yb:YAG/Cr,Yb:YAG self-Q-switched laser is expected.

Meanwhile, coating damage was occurred when the transmission of output coupler is equal to or less than 20% at high pump power levels owing to the high intracavity intensity with low transmissions of output coupler.

The laser emitting spectra show that the Yb:YAG/Cr,Yb:YAG self-Q-switched lasers oscillate in multi-longitudinal-mode for different output couplings. And number of longitudinal modes increases with absorbed pump power. Fig. 3 shows the laser emitting spectra of Yb:YAG/Cr,Yb:YAG self-Q-switched lasers under different absorbed power levels with $T_{OC} = 50\%$. Two longitudinal modes were obtained when the absorbed pump power was less than 1.6 W. There were three longitudinal modes oscillation when the absorbed pump power was between 1.6 and 3.8 W. Four longitudinal modes were observed when the absorbed pump power is higher than 3.8 W. Five longitudinal modes were obtained when the absorbed pump power reached 4.5 W. The separation

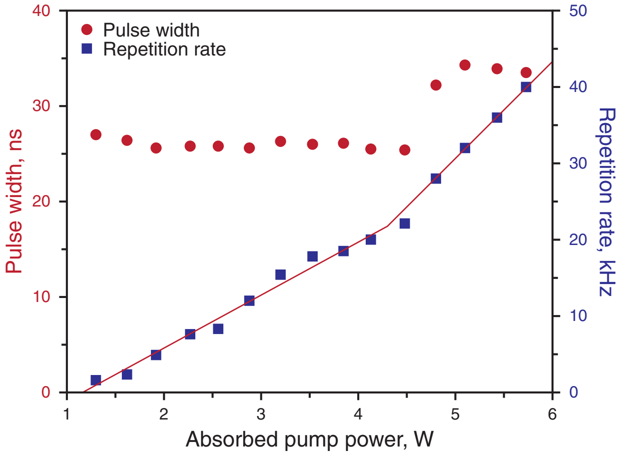

Figure 5 (online color at www.lphys.org) Pulse repetition rate and pulse width of Yb:YAG/Cr,Yb:YAG self-Q-switched laser as a function of the absorbed pump power with $T_{OC} = 50\%$. The lines show the changes of repetition rate with absorbed pump power

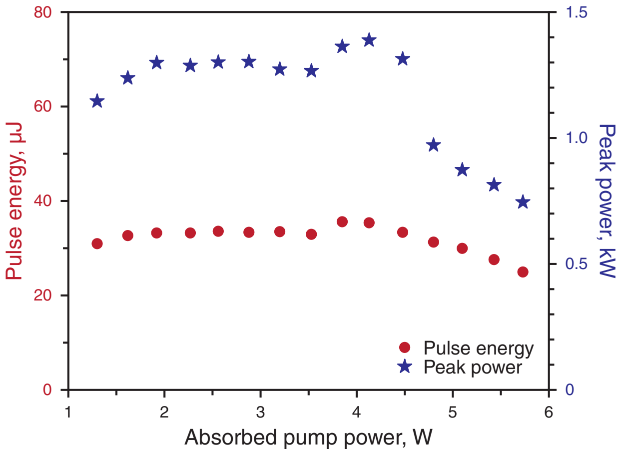

Figure 6 (online color at www.lphys.org) Pulse energy and peak power of Yb:YAG/Cr,Yb:YAG self-Q-switched laser as a function of the absorbed pump power with $T_{OC} = 50\%$

between each mode was measured to be about 0.574 nm, much wider (about 74 times of $\Delta\lambda_c$) than the free spectral range $\Delta\lambda_c = 0.0076$ nm in the laser cavity predicted by $\Delta\lambda_c = \lambda^2/2L_c$, [44] where L_c is the optical cavity length and λ is laser wavelength. The cause of wide separation between longitudinal modes is attributed to the intracavity tilted etalon effect of the Cr,Yb:YAG thin plate. The potential output longitudinal modes were selected by the combined etalon effect of the 0.5-mm-thick Cr,Yb:YAG and 1-mm-thick Yb:YAG thin plate as an intracavity etalon [44].

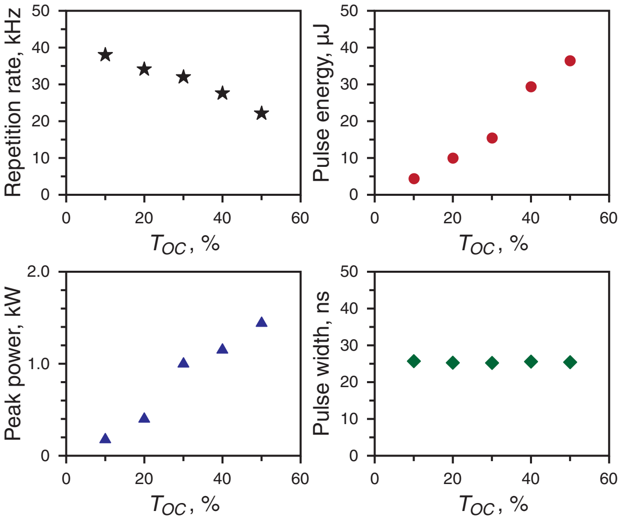

Figure 7 (online color at www.lphys.org) Pulse characteristics such as pulse repetition rate, pulse energy, peak power, and pulse width of Yb:YAG/Cr,Yb:YAG self-Q-switched lasers as a function of transmission of output coupler when the absorbed pump power was set to 4.5 W

Fig. 4 shows a typical train of laser pulse and the oscilloscope pulse profile for $T_{OC} = 50\%$ when the absorbed pump power is 4.5 W. The repetition rate was determined to be 24.1 kHz. The Yb:YAG/Cr,Yb:YAG self-Q-switched laser pulse profile with pulse energy of 37 μJ and pulse width (FWHM) of 26 ns is shown in Fig. 4b. Therefore, the peak power of self-Q-switched lasers is estimated to be 1.4 kW.

Fig. 5 shows the pulse repetition rate and pulse width of Yb:YAG/Cr,Yb:YAG self-Q-switched laser as a function of the absorbed pump power with $T_{OC} = 50\%$. The repetition rate increases linearly with absorbed pump power. However, the increase ratio of the repetition rate with absorbed pump power is different when the absorbed pump power is lower than 4.5 W comparing with that at high absorbed pump power levels. Repetition rate increases 7 kHz/W when the absorbed pump power is lower than 4.5 W, while repetition rate increases 12.7 kHz/W when the absorbed pump power is higher than 4.5 W. This may be caused by the strong multi-longitudinal modes competition induced by the strong thermal effect at high pump power level. The pulse width (FWHM) nearly keeps constant at different absorbed pump power levels when the absorbed pump power is kept lower than 4.5 W. Then the pulse width is broadened with further increase of the absorbed pump power owing to the strong thermal effect at high pump power levels. Fig. 6 shows the pulse energy and peak power of Yb:YAG/Cr,Yb:YAG self-Q-switched laser as a function of the absorbed pump power with $T_{OC} = 50\%$. Pulse energy and peak power increase with the absorbed pump power and tend to be saturated when the absorbed pump power is higher than 1.8 W and lower than 4.5 W. The pulse energy and peak power decrease with further increase of the absorbed pump power when the absorbed pump power is higher than 4.5 W. The pulse width, pulse energy, and peak power are nearly independent of the pump power for different transmission of output couplers when the absorbed pump power is lower than 4.5 W. According to the passively Q-switched laser theory [44–46], the pulse energy and the pulse width are determined by the initial transmission of 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. Fig. 7 shows the pulse characteristics such as repetition rate, pulse energy, peak power and pulse width of Yb:YAG/Cr,Yb:YAG self-Q-switched lasers as a function of transmission of output coupler (T_{OC}) when the absorbed pump power was set to 4.5 W. When the "Cr^{4+}"-ions saturable absorber was fully bleached under high intracavity laser intensity, repetition rate decreases with T_{OC}, pulse energy and peak power increase with T_{OC}, while pulse width is not so sensitive to T_{OC}. By varying the saturable absorber ("Cr^{4+}") concentration in Cr,Yb:YAG crystal and thickness of Cr,Yb:YAG crystal, the modulation depth can be changed, and the relevant pulse width and pulse energy can be achieved.

4. Conclusions

Efficient laser performance of self-Q-switched Cr,Yb:YAG lasers enhanced by bonding Yb:YAG crystal with a plano-concave resonator have been demonstrated for the first time. Best laser performance of Yb:YAG/Cr,Yb:YAG self-Q-switched lasers was achieved with 50% transmission of output coupler. Maximum output power of 1 W was obtained when the absorbed pump power of 5.4 W was applied, corresponding optical-to-optical efficiency of 18.5% was achieved with respect to the absorbed pump power. Slope efficiency of 25% was achieved with $T_{OC} = 50\%$. Laser pulses with pulse energy of 37 μJ, pulse width of 26 ns and peak power of 1.4 kW were achieved. Repetition rate of over 40 kHz was obtained. The lasers oscillate in multi-longitudinal-mode and the number of longitudinal modes increases with the pump power. Transmission of output coupler has great impact on the repetition rate, pulse energy and peak power, and has little affect on the pulse width of Yb:YAG/Cr,Yb:YAG self-Q-switched lasers. The performance of Yb:YAG/Cr,Yb:YAG self-Q-switched lasers can be further improved by varying the parameters of Yb:YAG crystal and Cr,Yb:YAG crystal.

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