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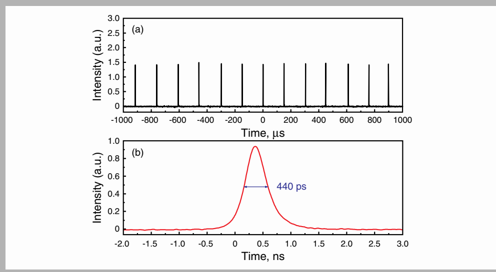
Abstract: Near-diffraction-limited longitudinal multimode self-Q-switched microchip Cr,Yb:YAG laser is obtained by using of a laser diode as a pump source at room temperature without cooling Cr,Yb:YAG sample. The output Q-switched traces are very stable, and the slope efficiency is as high as 18.5%. Laser pulses with 23.5-μJ pulse energy and 440-ps pulse duration were achieved which results in over 53 kW peak power at repetition rate of 6.6 kHz. The effect of the absorbed pump power on the laser characteristics and laser spectrum are addressed in details. The number of the longitudinal laser modes increases with the absorbed pump power.



The stable pulse train and the pulse profile of 440 ps pulse width

Stable laser-diode pumped microchip sub-nanosecond Cr,Yb:YAG self-Q-switched laser

J. Dong, [1,*] *A. Shirakawa,* [1] *S. Huang,* [1] *Y. Feng,* [1] *K. Takaichi,* [1] *M. Musha,* [1] *Ken-ichi Ueda,* [1] *and A.A. Kaminskii* [2]

[1] Institute for Laser Science, University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan
[2] Crystal Laser Physics Laboratory, Institute of Crystallography of the Russian Academy of Sciences, 59, Leninski pr., Moscow 119333, Russia

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1. Introduction

Robust, compact laser-diode pumped passively Q-switched microchip solid-state lasers of sub-nanosecond pulses with high energies and high peak powers (∼kW to MW) together with a diffraction-limited output beam can be potentially used in micromaching, remote sensing, target ranging, microsurgery, pollution monitoring, and so on. The passively Q-switched microchip lasers are usually operated by using a thin gain medium (Yb or Nd doped materials such as YAG, YVO_4 and $KGd(WO_4)_2$) bonded with saturable absorber such as semiconductor saturable-absorber mirror (SESAM) [1] and bulk Cr^{4+} doped crystals[2–5], or deposit Cr^{4+} films on the gain medium by molecular beam epitaxy (MBE)[6]. 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, such as high damage threshold, low cost, and simplicity. For microchip passively Q-switched laser operation, optically bonding saturable absorber and gain medium is difficult to fabricate and costs a lot, the easiest way to realize such goal is to co-dope saturable absorber and active ions into a host material to form a self-Q-switched laser material. The Cr,Nd:YAG crystal is one of the promising self-Q-switched laser material and microchip laser operation was demonstrated [7].

The low concentration of Nd in Cr,Nd:YAG crystal limits the microchip laser operation. The efficient laser operation requires absorbing enough pump power with short crystal length; the high concentration microchip laser materials are required to realize sub-nanosecond laser operation. Recently, some researchers reported chromium and ytterbium co-doped YAG crystal used as self-Q-switched laser material [8,9]. Laser diode pumped Yb:YAG lasers have several advantages relative to Nd:YAG lasers, such as a long storage lifetime (951 μs) [10], a very low quantum defect (8.6%), resulting in three times less heat generation during lasing than comparable Nd-based laser systems [11], broad absorption width which is approximately eigh-

* Corresponding author: e-mail: jundong_99@yahoo.com

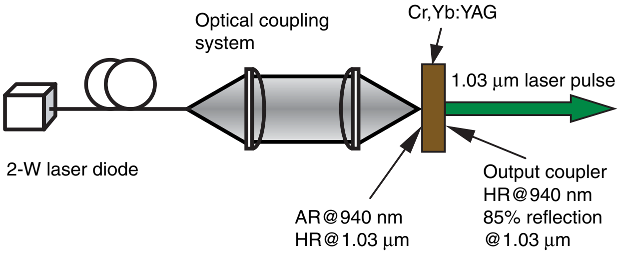

Figure 1 (online color at www.lphys.org) Schematic of laser-diode end-pumped Cr,Yb:YAG self-Q-switched microchip laser

teen times broader than the 808 nm absorption feature in Nd:YAG and therefore the Yb:YAG system is less sensitive to diode wavelength specifications [12], a relatively large emission cross section [13], and easy growth of high quality and moderate concentration crystal without concentration quenching. The self-Q-switched Cr,Yb:YAG laser was first demonstrated by using Ti:sapphire laser as a pumping source [14]. The self-Q-switched laser pulse output with pulse width of 0.5 ns was achieved recently with 750 μm thickness Cr,Yb:YAG crystal [15], but the average output power is very low and coating of the crystal was damaged very quickly, so this laser can not be used in practice. The low efficient operation is caused by the thin crystal (0.75 mm) doped with low Yb^{3+} concentration (5 at.%) and the quality of the crystal because the defect in the crystal will increase with the concentration of Cr. The cause of the optical damage of the dielectric coatings may be due to high intracavity fluence in 0.5 ns pulse width. There are two ways to solve this problem, one is to generate longer output pulse width with low concentration of Cr^{4+}, and the other is to increase the area of the emitting beam on the microchip laser output mirror and the transmission of the output coupler. The emitting beam diameter can be increased by increasing the pump beam diameter for the planar-parallel microchip laser. Therefore, 1-mm Cr,Yb:YAG crystal doped with 10 at.% Yb concentration and 0.025 at.% Cr (5 at.% Yb and 0.5 at.% Cr doped Cr,Yb:YAG crystal in [15]) was chosen as a laser gain medium, which will absorb about 86% incident pump power with two-pass pumping configuration and keep the initial transmission around 90%. In this paper, laser-diode pumped Cr,Yb:YAG microchip self-Q-switched laser with stable, near-diffraction-limit output is reported, laser pulses with 440-ps pulse duration and 23.5-μJ pulse energy were obtained at 6.6 kHz repetition rate, which results in a peak power of over 53 kW. The slope efficiency is as high as 18.5%, the optical-to-optical efficiency is about 10%.

2. Experiments

The Cr,Yb:YAG crystal used in this experiment was grown by the standard Czochralski method. Cr^{4+} was substituted into distorted tetrahedral Al site [16], therefore a charge compensator was required, and $CaCO_3$ was added for that purpose. The nominal concentrations of chromium and ytterbium in the Cr,Yb:YAG crystal were 0.025 and 10 at.%, respectively. The absorption and emission spectra were reported in [8] and [9]. The absorption coefficient is 12.5 cm^{-1} at the peak wavelength of 941 nm; the absorption coefficient at 937.5 nm is about 10 cm^{-1}. The absorption coefficient at 1.03 μm of Cr^{4+} (the self-absorption of Yb^{3+} at 1.03 μm was subtracted by comparing the absorption spectrum of Cr,Yb:YAG doped with 10 at.% Yb^{3+} and Yb:YAG doped with 10 at.% Yb^{3+}) is 1.21 cm^{-1}. The emission cross section of Cr,Yb:YAG is about 2.5×10^{-20} cm^2, the fluorescence lifetime is about 584 μs [8], which is shorter than that of Yb:YAG crystal (951 μs) [10]. The laser diode pumped mirochip Cr,Yb:YAG self-Q-switched laser experimental setup is shown in Fig. 1. A 1 mm-thickness Cr,Yb:YAG crystal was polished to a plane-plane geometry as a laser resonator. The planar rear surface is coated for high transmission (>90%) at 940 nm and total reflection (>97%) at 1030 nm. The planar front surface serving as output coupler is coated for 85% reflection at 1030 nm and total reflection (>98%) at 940 nm. A 2-W fiber-coupled 937.5 nm laser diode with a core diameter of 102 μm and numerical aperture of 0.15 was used as the pump source. The coupling optics (two focus lens with focus length of 8 mm) was used to focus the pump beam into the crystal rear surface. After the coupling optics, there is about 92% pump power incident on the Cr,Yb:YAG crystal and the pump light spot in Cr,Yb:YAG is about 100 μm in diameter. The Cr,Yb:YAG laser operation was performed at room temperature without cooling Cr,Yb:YAG crystal. The Q-switched pulse profiles were recorded by using an fiber-coupled InGaAs photodiode (Model DSC40S from Discovery Semiconductor) with a bandwidth of 16 GHz, and a Tektronix TDS7704B digital phosphor oscilloscope of 7 GHz sampling rate in the single-shot mode. The laser spectrum was analyzed by using an ANDO AQ6317 optical spectrum analyzer. The laser output beam profile near the output coupler and far field was monitored by using the CCD camera, the beam diameter and beam quality M^2 can be determined.

3. Results and discussion

The repetitively self-Q-switched laser pulse trains were observed when the absorbed pump power is above 680 mW, the output laser pulse train was stable with further increasing the pump power, and the variation of the pulse amplitude was within 5% even at lower pump power. Fig. 2 shows a train of the laser pulse and the oscilloscope pulse profile when the absorbed pump power is 1520 mW, the pulse-to-pulse amplitude fluctuation is less than 1% (as shown in Fig. 2a), the repetition rate was determined to be 6.6 kHz. The self-Q-switched pulse profile with output pulse energy of 23.5 μJ and pulse duration (FWHM) of 440 ps is shown in Fig. 2b. So the peak

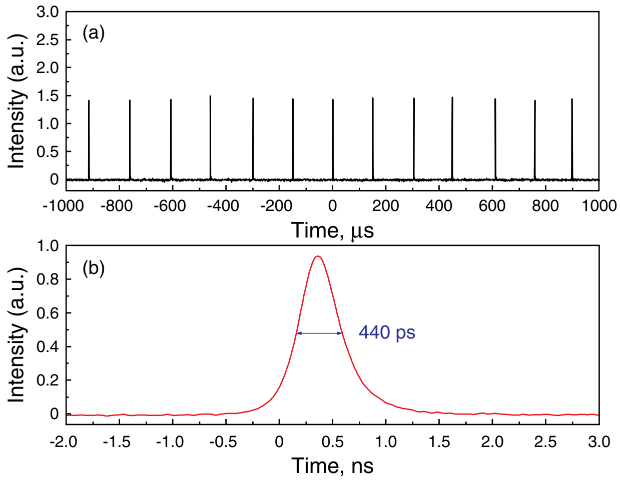

Figure 2 (online color at www.lphys.org) (a) Laser pulse train and (b) the pulse waveform when the absorbed pump power is 1520 mW, the pulse width (FWHM) is 440 ps; the repetition rate is 6.6 kHz

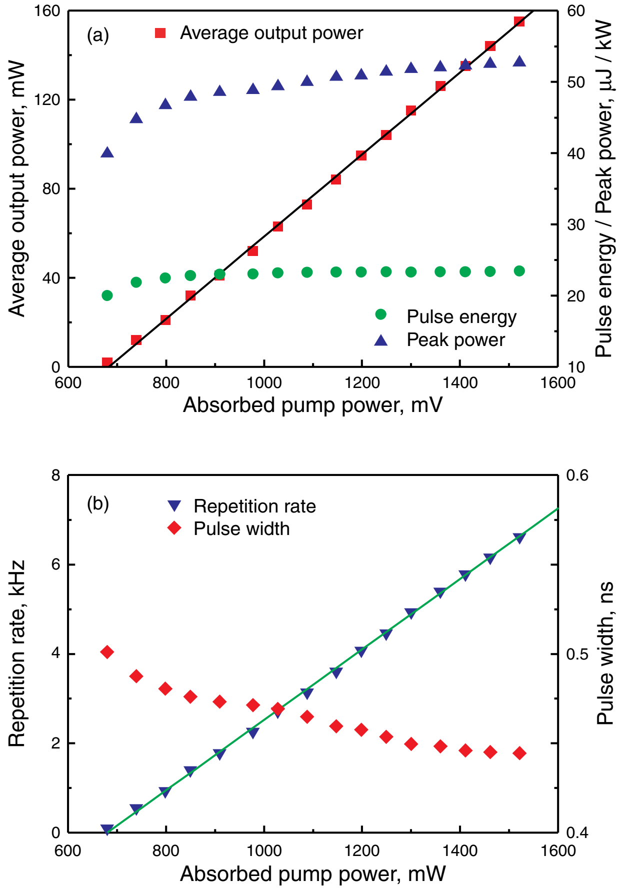

Figure 3 (online color at www.lphys.org) (a) The average output power, the pulse energy and the peak power, (b) the pulse width (FWHM) and the repetition rate of Cr,Yb:YAG self-Q-switched laser as a function of the absorbed pump power

power is estimated to be over 53 kW. The average output power, pulse energy, peak power, pulse width and repetition rate as a function of the absorbed pump power is shown in Fig. 3, the average output power increases linearly with the absorbed pump power, and there is no pump saturation although the Cr,Yb:YAG crystal is not temperature controlled. Therefore, the average output power can be scaled higher with higher pump power. The highest output power of 156 mW was obtained at maximum absorbed pump power of 1520 mW, the slope efficiency is as high as 18.5%, the maximum optical-to-optical efficiency is about 10% when absorbed pump power is 1520 mW. Owing to the nature of quasi-three-level system of Yb^{3+}, there is stronger reabsorption at laser wavelength, which depends strongly on the temperature of the Cr,Yb:YAG, the higher the temperature, the stronger absorption occurs, the efficient laser operation can be achieved by cooling the sample, the optical and thermal properties of ytterbium-doped YAG crystal also improve at low temperature [13]. Room temperature operation of Cr,Yb:YAG self-Q-switched laser with low-power (several watts), high brightness laser-diode as pump source makes this crystal a potential candidate for compact, robust laser for some applications without cooling system. The pulse energy increases with the pump power when the pump power is above the pump power threshold, then keeps nearly as a constant when the absorbed pump power is above 900 mW. The peak power of Cr,Yb:YAG self-Q-switched laser increases quickly with the pump power at lower pump power range and then increases slowly at the higher pump power range (above 900 mW). The repetition rate increases linearly with the absorbed pump power from several hundreds Hz to 6.6 kHz, which is in agreement with the theory prediction. The pulse width (FWHM) decreases very slowly from 500 ps to 440 ps with the absorbed pump power. According to the passively Q-switched laser theory [17], the pulse energy and the pulse width are determined by the saturable absorber parameters 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. There is no dielectric coating damage observed throughout the laser experiments although shorter pulse width (440 ps) is obtained, this is attributed to the decrease of the Cr concentration in Cr,Yb:YAG crystal (0.025 at.% vs 0.5 at.% [15]), the defects introduced by the Cr concentration is decreased, and the same time the modulation depth (initial transmission of 89%) was nearly kept the same with 1 mm thickness of Cr,Yb:YAG crystal. In addition, increase of the concentration of Yb to 10 at.% and the length of the crystal to 1 mm absorbs more pump power and makes laser more efficient. The experimental results show that concentration of Cr,Yb:YAG crystal has great effect on the laser performance. Stable laser operation without dielectric coating damage was achieved by

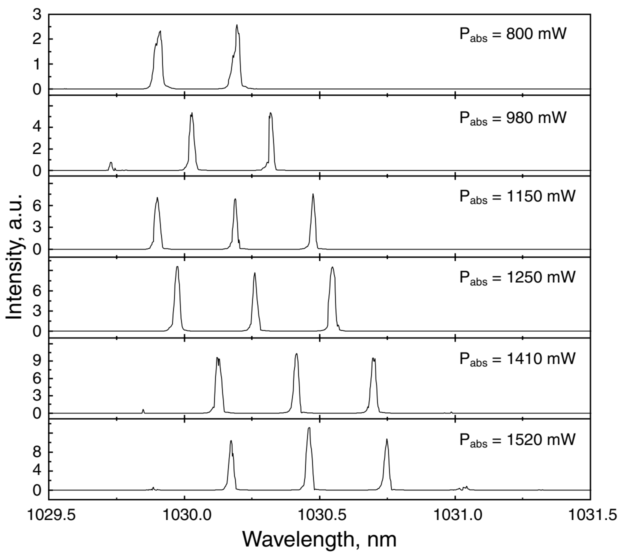

Figure 4 Laser spectra around 1030 nm of Cr,Yb:YAG self-Q-switched laser under different pump power. The resolution of the measurement is 0.01 nm

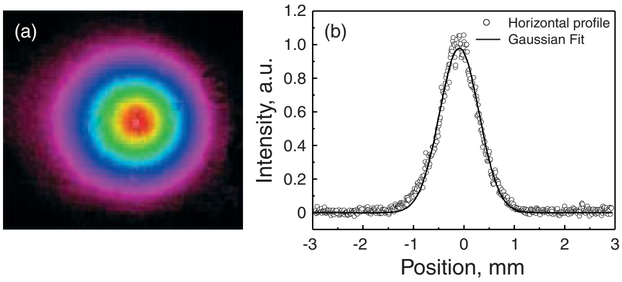

Figure 5 (online color at www.lphys.org) (a) Beam profile measured by a CCD camera of laser output. (b) Horizontal slice through center of the beam profile with a Guassian fit

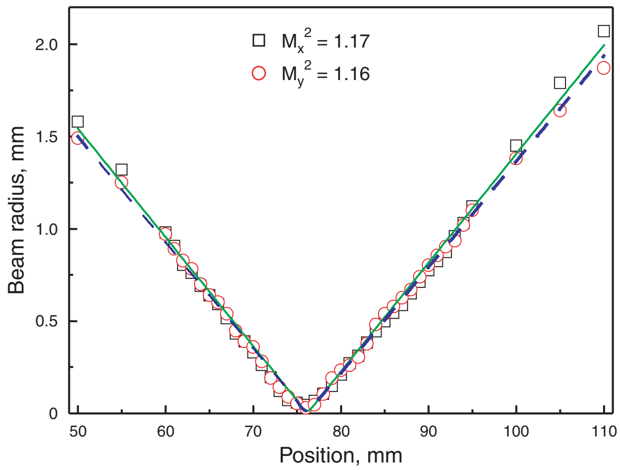

Figure 6 (online color at www.lphys.org) The beam radii near the focus point for laser-diode pumped Cr,Yb:YAG self-Q-switched laser. The output beam was focused by a lens of 100 mm focal length

decreasing the concentration of Cr in Cr,Yb:YAG crystal. The quality of Cr,Yb:YAG increases by decreasing the concentration of Cr, which results in the higher efficient operation. At the same time the crystal length and the output coupler reflectivity at 1030 nm also have contributions to avoid the dielectric coating damage.

Meanwhile, the laser spectrum of this self-Q-switched laser is longitudinal multi-mode (around 1030 nm) oscillation, when the power is over threshold, there is two-frequency oscillation, further increase pump power, there are three-, four-frequency oscillation, there is five-frequency oscillation when the absorbed pump power is over 1500 mW, as shown in Fig. 4. The separation of each frequency under different pump power is about 0.29 nm, the linewidth at each frequency is measured to be 0.02 nm. According to the laser resonator theory [17], the separation of the longitudinal modes in a laser cavity is given by $\Delta\lambda = \lambda^2/2L_c$, where L_c is the optical length of the resonator. For the 1 mm Cr,Yb:YAG planar-parallel resonator studied here, $\Delta\lambda$ was calculated to be 0.2915 nm with the laser wavelength of 1030 nm, the experimental data is in good agreement with the theory prediction. The output Q-switched pulses are linearly polarized along either of the mutually orthogonal axes, with an extinction ratio of 30:1. The polarization does not change with the rotation of the Cr,Yb:YAG sample. Because there is no polarized pump source used in the experiment, the polarization of this laser may be caused by the anisotropy saturation absorption of Cr^{4+} ions [7,18]. The laser output power beam profile as well as a horizontal slice through the center is shown in Fig. 5, the output beam fits well to the Gaussian profile (Fig. 5b). Measured position-dependent beam radius near the focus are shown in Fig. 6, the beam quality factor M_x^2 and M_y^2 values were determined to be 1.17 and 1.16, respectively. Near diffraction-limited output beam quality was achieved in such compact Cr,Yb:YAG self-Q-switched laser. The output beam diameter near the output mirror was measured to be 120 μm.

4. Conclusions

In conclusion, by using of a laser-diode as a pump source, a near-diffraction-limited self-Q-switched laser output from Cr,Yb:YAG crystal is demonstrated, and the output Q-switched pulse trains are very stable. The absorbed pump power threshold is 680 mW, the slope efficiency is as high as 18.5%, the laser pulses with 440-ps pulse duration and 23.5-μJ pulse energy were obtained at repetition rate of 6.6 kHz, resulting in a peak power of over 53 kW. The pulse duration decreases slowly with the absorbed pump power and the pulse energy and the peak power increase slowly at high pump power. The repetition rate increases linearly with the pump power. The high efficient laser performance is expected by using cooling system for Cr,Yb:YAG crystal. The average output power, pulse energy can be scaled by increasing the pumping area of the gain medium by using top-hat laser diode as pumping source. The multi-frequency Cr,Yb:YAG microchip Q-switched laser with high energy and short pulse output at several kilohertz may be a good source for inertia fusion energy.

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