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Optics Communications 256 (2005) 158–165

OPTICS COMMUNICATIONS

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Multi-longitudinal-mode oscillation of self-Q-switched Cr,Yb:YAG laser with a plano-concave resonator

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Received 17 March 2005; received in revised form 20 June 2005; accepted 22 June 2005

Abstract

Stable longitudinal multi-mode chromium and ytterbium co-doped Cr,Yb:YAG self-Q-switched laser formed by a plano-concave resonator has been demonstrated at room temperature without cooling system. An average output power of as much as 70 mW at 1.03 μm with a pulse width (FWHM) as short as 12.3 ns was obtained with 5% transmission output coupler. High beam quality ($M^2 < 2.4$) output with transverse gaussian profile was obtained. The non-linear mode coupling effects of this longitudinal multi-mode laser was investigated and stable pulse sequence was attributed to the non-linear mode coupling effects between main mode oscillation and the side-mode oscillation.

PACS: 42.55.Xi; 42.60.Gd; 42.65.Sf; 42.70.Hj

Keywords: Laser-diode-pumped-laser; Self-Q-switch; Cr,Yb:YAG; Non-linear mode coupling

1. Introduction

Laser-diode pumped passively Q-switched solid-state lasers are currently explored extensively and used for miniature or microchip lasers capable of delivering high peak power (~kW to MW) at high repetition rate and nanosecond or sub-nanosecond pulse width. These lasers can be potentially used in micromaching, remote sensing, target ranging, microsurgery, pollution monitoring, and so on. The passively Q-switched lasers are usually operated by using a thin gain medium bonded with saturable absorber such as semiconductor saturable-absorber mirror (SESAM) [1] and bulk Cr^{4+} doped crystals [2,3], or deposit Cr^{4+} films on the gain medium by molecular beam epitaxy (MBE) [4]. Compared with SESAM or the saturable absorber film deposited on the surface of the gain medium, Cr^{4+} doped bulk crystals as saturable

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doi:10.1016/j.optcom.2005.06.050

absorber have several advantages, such as a 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 in 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 monolithic laser operation was demonstrated [5]. 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 subnanosecond laser operation. Recently, some researchers reported chromium and ytterbium codoped YAG crystal used as self-Q-switched laser material [6,7]. Compared with Cr,Nd:YAG self-Q-switched laser crystal, Cr,Yb:YAG crystal has several advantages for microchip laser operation. First, high ytterbium concentration and high quality Cr,Yb:YAG can be grown by traditional Czochralski (CZ) method. Second, the optical properties of Yb^{3+} such as smaller emission cross-section and longer lifetime are more suitable to realize high energy and high peak power operation. Third, the thermal properties of Cr,Yb:YAG is better than that of Cr,Nd:YAG crystal. The self-Q-switched Cr,Yb:YAG laser was first demonstrated by using Ti:sapphire laser as a pumping source [8]. The self-Q-switched laser pulse output with pulse width of 500 ps was achieved recently with 750-μm thickness Cr,Yb:YAG crystal [9]. However, the average output power is very low and coating of the crystal was damaged, and there is no detail reports on the laser characteristics. The low doping concentration of ytterbium (5 at.%) in Cr,Yb:YAG and thin gain medium (0.75 mm) absorbs only 50% incident pump power which results the low output power and low efficiency. The cause of the coating damage may be due to the high fluence inside the cavity with 0.5-ns pulse width. The coating damage problem can be solved by enlarging the pulse width, which can be realized by using longer cavity. Because the broad emission bandwidth of ytterbium-doped Cr,Yb:YAG crystal (about 8 nm), the longitudinal multi-mode oscillation will be the dominant oscillation owing to the spatial hole burning effect. There are some reports on the non-linear mode coupling effects of multi-mode laser with intracavity doubling crystal [10], saturable absorber [11] and gain and loss modulation [12]. The non-linear mode coupling effects such as antiphase states in multi-mode solid-state lasers have been used for encoded information transmission [13]. In this paper, laser-diode pumped Cr,Yb:YAG self-Q-switched laser formed by a plano-concave resonator with good beam quality output is reported, laser pulses with 12.3-ns pulse duration and 11.2-μJ pulse energy were obtained at 6.25 kHz repetition rate, which results in a peak power of about 910 W. The non-linear mode coupling effects of this longitudinal multimode oscillation were also addressed.

2. Experiments

The Cr,Yb:YAG crystal used in this experiment was grown by the standard Czchralski method. Cr^{4+} was substituted into distorted tetrahedral Al site [14], 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 of Cr,Yb:YAG crystal at room temperature were shown in Fig. 1. The absorption coefficient is 12.8 cm^{-1} at the peak wavelength of 941 nm. 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 [7], which is shorter than that of Yb:YAG crystal (951 μs).The schematic of laser diode CW-pumped Cr,Yb:YAG self-Q-switched laser is shown in Fig. 2. A 1-mm planar–planar Cr, Yb:YAG crystal doped with 10 at.% Yb and 0.025 at.% Cr was used as a laser gain medium. One surface of the Cr,Yb:YAG crystal is coated for anti-reflection (>97%) at 940 nm and total

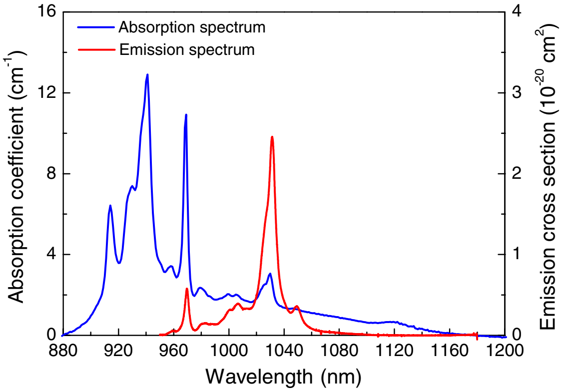

Fig. 1. Absorption coefficient (blue) and effective emission cross-section (red) of Cr,Yb:YAG crystal doped with 10 at.% Yb and 0.025 at.% Cr at room temperature. (For interpretation of the references to the colour in this figure legend, the reader is referred to the web version of this article.)

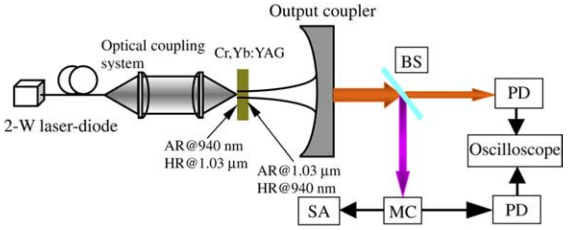

Fig. 2. The schematic of the laser diode pumped Cr,Yb:YAG self-Q-switched laser. BS, beam splitter; PD, photodiode; MC, monochromator; SA, spectrum analyzer.

reflection (>99.9%) at 1030 nm to act as a cavity mirror of the laser (input mirror). The other surface of the Cr,Yb:YAG is coated for anti-reflection (>97%) at 1030 nm to reduce the cavity loss and total reflection (>99%) to increase the absorbed pump power. The output coupler is a concave mirror with 70-mm curvature and reflectivity is 98% and 95% at 1.03 μm. The overall cavity length is ~35 mm. A 2-W fiber-coupled 937.5-nm multi-mode laser diode with a core diameter of 102 μm and numerical aperture of 0.15 was used as the pump source. The light from the laser diode was collimated and focused by a pair of 8-mm-focal-length lens. 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. About 85% of the incident pump power was absorbed by the Cr,Yb:YAG crystal. The laser spectrum was analyzed by using an ANDO AQ6317 optical spectrum analyzer. In order to study the dynamics of different sets of modes separately, a monochromator was used to detect each mode by setting the center wavelength at the peak position of each mode. The Q-switched pulses of the total and a specific mode were recorded by using fast InGaAs detectors of less than 1-ns rise time and a 500-MHz Tektronix TDS 3052B digitizing oscilloscope. 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 discussions

The initial transmission of Cr^{4+} saturable absorber at 1.03 μm in the Cr,Yb:YAG crystal co-doped with 0.025 at.% Cr and 10 at.% Yb is about 89%. The repetitively self-Q-switched laser pulse trains were observed when the absorbed pump power was above 350 mW for 2% transmission of the output coupler. The output laser pulse train was stable with further increasing the pump power and the fluctuation of the pulse amplitude was within 5% even at lower pump power. Fig. 3 shows a typical train of the laser pulse and the oscilloscope pulse profile for 5% transmission of the output coupler when the absorbed pump power is 980 mW. The repetition rate can be determined to be 6.25 kHz. The self-Q-switched pulse profile with output pulse energy of 11.2 μJ and pulse duration (FWHM) of 12.3 ns is shown in Fig. 3(b). So the peak power is estimated to be about 915 W.

The pulse energy was determined from the average output power and pulse repetition rate. The peak power was determined from the pulse energy and pulse width. The average output power as a function of the absorbed pump power is shown in Fig. 4. The average output power increases linearly with the absorbed pump power in this pump power range. However, there is coating damage for 2% transmission of the output coupler when the absorbed pump power is higher

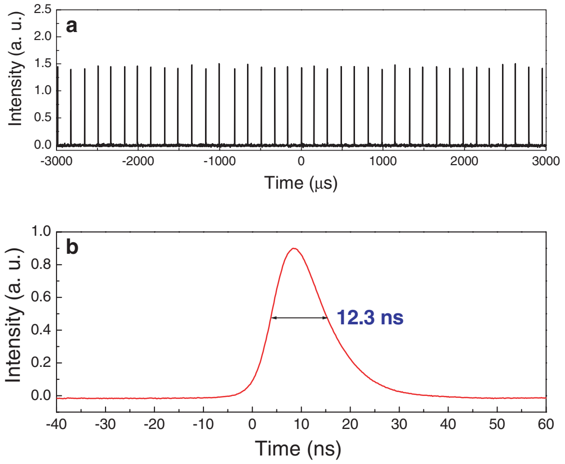

Fig. 3. (a) Laser pulse train and (b) the pulse waveform when the absorbed pump power is 980 mW for $T = 5\%$ of the output coupler, the pulse width (FWHM) is 12.3 ns; the repetition rate is 6.25 kHz.

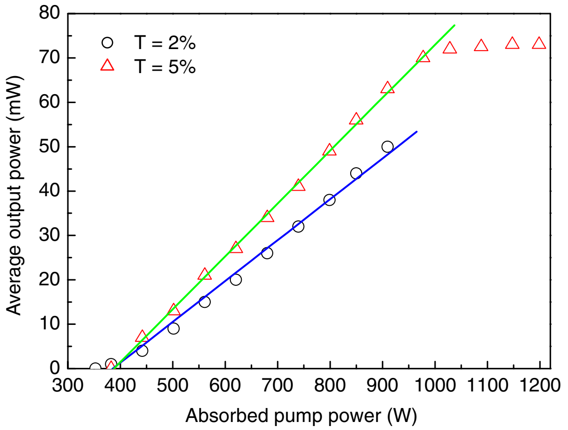

Fig. 4. Average output power of Cr,Yb:YAG self-Q-switched laser with different transmissions of the output coupler as a function of the absorbed pump power. The lines are the linear fitting the experimental data. There is coating damage occurrence when the absorbed pump power is higher than 920 mW for $T = 2\%$.

than 920 mW, this may be the cause for the high reflectivity of the output coupler, which results in very high photon density in the laser cavity, hence the coating is damaged. For 5% transmission of the output coupler, there is no coating damage even in the more high pump power, but there is saturation for the average output power when the absorbed pump power is higher than 1 W. The damage threshold for the dielectric coating of Cr,Yb:YAG crystal was estimated to be 1.25 J/cm^2 for 12-ns pulse width according to the experimental data of the coating damage occurring for $T = 2\%$. The highest fluence intensity inside the laser cavity is estimated to be 0.71 J/cm^2 for 12-ns pulse width for $T = 5\%$, which is lower than the coating damage threshold. Therefore, there is not coating damage observed during the experiment for $T = 5\%$. The laser saturation intensity at 1030 nm of Cr, Yb:YAG is calculated to be 14 kW/cm^2 according to the optical parameters of Cr,Yb:YAG crystal studied here [7]. The highest intracavity average power intensities are estimated to be 8 kW/cm^2 for $T = 2\%$ and 4.5 kW/cm^2 for $T = 5\%$, respectively, which are lower than the laser saturation intensity, so there should be no saturation occurrence for both transmissions of the output couplers. However, there is more heat generated inside the gain medium when the pump power is high, the effect of the temperature on the thermal population distribution becomes very strong for Yb^{3+} doped YAG quasi-three-level laser system. The lower laser-level thermal population increases with the temperature, which makes the inversion population density decrease under certain pump power. Therefore, the decrease of the inversion population owing to the increase of the temperature will make the average output power do not increase linearly with the pump power. There may be a nearly constant net inversion population owing to the increase of the thermal population of lower laser-level and the population in the upper laser-level pumped by the pump power. So the average output power does not increase with the pump power, in other word, it is saturated as observed in the experiment for 5% transmission of the output coupler. The output power will decrease even with further increase of the pump power because thermal population is higher with temperature due to the higher pump power. From these experimental results, we can see that higher transmission of the output coupler should be used to achieve high average output power and avoid the damage of the coating of the crystal. The absorbed pump power thresholds are about 350 and 380 mW for 2% and 5% transmission of the output coupler, respectively. The highest output power of 50 mW was obtained at maximum absorbed pump power of 910 mW for $T = 2\%$ without the coating damage. The slope efficiency is as high as 9.2% and the maximum optical-to-optical efficiency is about 5.5% for $T = 2\%$ when absorbed pump power is 910 mW. The highest average output power of 70 mW was achieved when the absorbed pump power is about 980 mW for $T = 5\%$, the slope efficiency increases to 12% compared with that of $T = 2\%$, the maximum optical-to-optical efficiency is about 7%. Owing to the nature of quasi-three-level system of Yb^{3+}, there is stronger re-absorption at laser wavelength, which depends strongly on the temperature of the Cr,Yb:YAG, the higher the temperature, the stronger absorption occurs. Because the optical and thermal properties of ytterbium-doped YAG crystal improves at low temperature [15,16], the efficient laser operation could be achieved by cooling the sample. The low threshold and high efficient performance of Cr,Yb:YAG crystal can be obtained at low temperature. The efficient operation of Yb:YAG crystal at liquid nitrogen temperature has been demonstrated [17,18]. Room temperature operation of Cr,Yb:YAG self-Q-switched laser with low-power, high brightness laser-diode as pump source makes this crystal a potential candidate for compact, robust laser for some applications without cooling system.

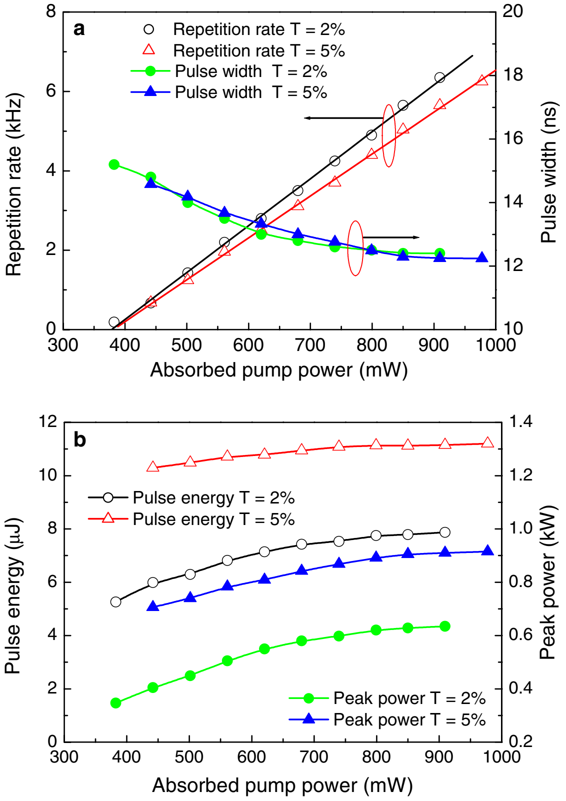

Fig. 5. (a) The repetition rate and the pulse width (FWHM). (b) The pulse energy and the peak power of Cr,Yb:YAG self-Q-switched laser as a function of the absorbed pump power for different transmissions of the output coupler.

Fig. 5 shows the repetition rate, the pulse with (FWHM), the pulse energy and the peak power of self-Q-switched Cr,Yb:YAG laser as a function of the absorbed pump power. The repetition rate increases linearly with the absorbed pump power from several hundreds Hz to 6.3 kHz, which is in agreement with the theory prediction. The pulse width (FWHM) decreases very slowly from 15.5 to 12.3 ns with the absorbed pump power and nearly keeps constant at the higher pump power range, and has very smaller difference for two transmissions of the output coupler, as shown in Fig. 5(a). The pulse energy increases with the pump power, the highest pulse energy of 7.9 and 11.2 μJ was obtained for $T = 2\%$ and $T = 5\%$ of the output coupler, respectively. The peak power of Cr,Yb:YAG self-Q-switched laser increases with the pump power. The highest peak powers of 635 and 915 W were obtained for $T = 2\%$ and $T = 5\%$ of the output coupler, respectively. There is a tendency of saturation for both the pulse energy and the peak power with the absorbed pump power. According to the passively Q-switched laser theory [19], 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. By varying the saturable absorber (Cr^{4+}) concentration in Cr,Yb:YAG crystal, the modulation depth can be changed, and the relevant pulse width and pulse energy can be achieved.

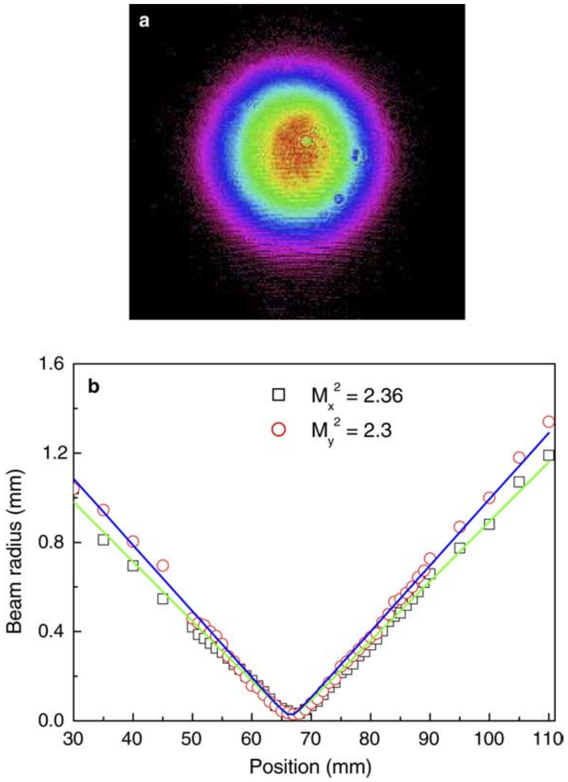

Fig. 6. (a) Beam profile measured by a CCD camera of laser output and (b) the beam radii near the focus point for laser-diode pumped Cr,Yb:YAG self-Q-switched laser. The output beam was focused by a lens of 100-mm focal length.

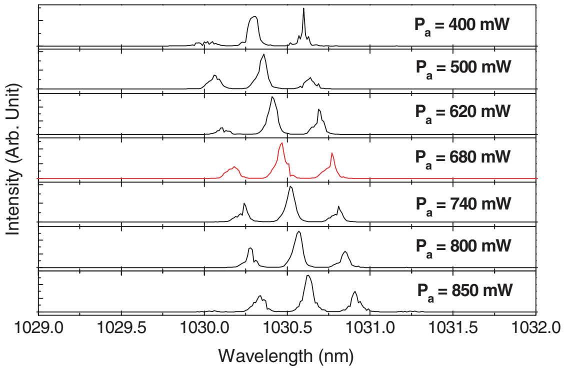

Fig. 7. Laser spectra around 1030 nm of Cr,Yb:YAG self-Q-switched laser with 5% transmission of the output coupler under different pump power. The resolution of the measurement is 0.01 nm.

The output self-Q-switched laser beam is transverse TEM$_{00}$ mode with a gaussian profile as shown in Fig. 6(a). Measured position-dependent beam radius near the focus are shown in Fig. 6(b), the beam quality factor M_x^2 and M_y^2 values were determined to be 2.3, 2.36, respectively. At the same time, the beam diameter near the output coupler was measured to be 220 μm.

Meanwhile, the measured laser spectrum shows that this self-Q-switched laser is multi-longitudinal-mode (around 1030 nm) oscillation for both transmissions of the output coupler. When the power is over threshold, there are three-frequency oscillation for $T = 5\%$, further increase pump power, three modes oscillation shifts to the longer wavelength, there is five-mode oscillation when the absorbed pump power is over 850 mW, as shown in Fig. 7. The wavelength of each mode shifts to longer wavelength with increasing pump power, this is caused by the increase of the temperature of the gain medium induced by the increase of the pump power. The emission spectrum of Yb:YAG and Cr,Yb:YAG crystal shifts to the longer wavelength with the increase of the temperature [15,16], this is an intrinsic property of the quasi-three-level system for Yb^{3+} doped materials. Although there is thermal expansion of the gain medium, the effect on the laser spectrum of Yb^{3+} doped YAG crystal is smaller comparing to the effect of the temperature dependent emission spectrum. The separation of each mode under different pump power in Fig. 7 is about 0.3 nm, the linewidth of each mode is measured to be from 0.05 to 0.09 nm. According to the laser resonator theory [19], 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 laser cavity with a length of 35 mm, the separation of the longitudinal modes is about 0.015 nm, which is narrower than the measured value. Mode selection in this multi-mode laser is mainly determined by the gain medium used in the experiment. The 1-mm Cr,Yb:YAG planar–parallel gain medium studied here, $\Delta\lambda$ was calculated to be 0.2915 nm with the laser wavelength of 1030 nm, which has a good agreement with the experimental data. Stable three longitudinal modes oscillation in this laser cavity can be achieved when the absorbed pump power is below 800 mW. This result shows that competition between the modes is very strong, only those preferentially modes oscillate. 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 and no polarization elements in the cavity, the polarization of this laser may be caused by the anisotropy saturation absorption of Cr^{4+} ions [5,20].

Fig. 8 shows the typical oscilloscope traces of Q-switched pulse trains for: (a) total pulse sequence; (b) 1030.18 nm; (c) 1030.47 nm; and (d) 1030.77 nm at absorbed pump power of 680 mW. The time interval between pulses for the main mode (1030.47 nm) is the same as that of the total pulse (as shown in Fig. 8(c) and (a)). The pulse repetition rate is mainly determined by the main mode oscillation. There is a strong fluctuation of the amplitude of each pulse for main mode. The pulse trains of two side modes are totally different from that of main mode, the time interval between each mode for the side mode (1030.19 or 1030.77 nm) is nearly 4 times longer than that of the total output pulses. And there is also amplitude fluctuation and the repetition rate jitter, so the recorded time interval between pulses for two side modes has some discrepancies. Although the time interval between two side modes is nearly 4 times longer than the main mode, the total output laser pulse train is still very stable. Because the pulse trains of each mode were recorded separately, we can not determine the relative phases between each mode with present experimental data. However, from the measurement of the pulse trains of each mode and the total pulse train, we can see that there are some non-linear relationships between each mode, and the contribution of the each mode to the total pulse output train will make stale pulse train output. This stability of the total pulse sequences can be attributed the non-linear mode coupling effect between each mode [21]. Comparing pulse sequences of total output pulse and those of each mode, we can see that there is repetition rate jitter occurrence, so the recorded pulse trains have some time fluctuations. Because the pulse trains of two side modes are not measured synchronically, the exact relationship between each mode is not so clear, maybe there is antiphase state, or displacing one period of the total output pulse. The mechanism of such interesting phenomena will be investigated further by measuring the pulse sequences of each mode synchronically in near future.

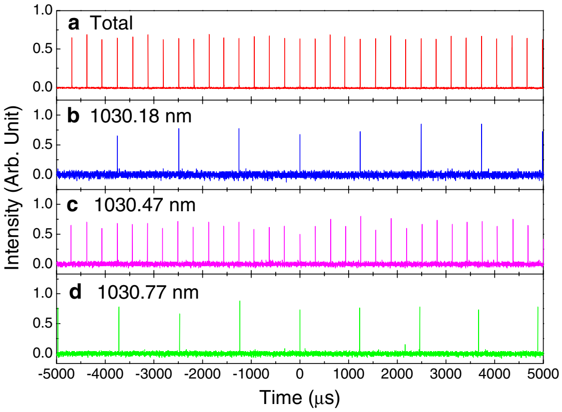

Fig. 8. Oscilloscopic trace of a train of Q-switched pulses at absorbed pump power of 680 mW for different wavelengths with three modes oscillation.

4. Conclusions

The laser-diode pumped Cr,Yb:YAG self-Q-switched laser formed by plano-concave cavity has been demonstrated at room temperature without water cooling system. Passively Q-switched laser pulses with pulse energy of 11.2 μJ and a pulse width (FWHM) of 12.3 ns at repetition rate of 6.3 kHz were obtained. The highest average output power of 70 mW was achieved with a slope efficiency of approximately 12.5% and an optical-to-optical efficiency of 7%. The stable three-mode oscillation in a large pump range was observed. The pulse repetition rate was mainly determined by the main mode oscillation, the stable pulse output was attributed to the non-linear mode coupling effect between the main mode and side modes. The gaussian beam profile output with high beam quality was achieved in this laser. The efficiency of such laser can be improved by using cooling system because the temperature has a great impact on the laser performance for quasi-three-level Yb^{3+} system.

Acknowledgments

This work was supported by the 21st Century Center of Excellence (COE) program of Ministry of Education, Science and Culture of Japan. J. Dong thank Prof. P. Deng of Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, for providing the Cr,Yb:YAG samples.

References

[1] G.J. Spuhler, R. Paschotta, M.P. Kullberg, M. Graf, M. Moser, E. Mix, G. Huber, C. Harder, U. Keller, Appl. Phys. B 72 (2001) 285.
[2] J. Dong, P. Deng, Y. Liu, Y. Zhang, J. Xu, W. Chen, X. Xie, Appl. Opt. 40 (2001) 4303.
[3] Y. Kalisky, C. Labbe, K. Waichman, L. Kravchik, U. Rachum, P. Deng, J. Xu, J. Dong, W. Chen, Opt. Mater. 19 (2002) 403.
[4] O.A. Buryy, S.B. Ubiszkii, S.S. Melnyk, A.O. Matkovshii, Appl. Phys. B 78 (2004) 291.
[5] J. Dong, P. Deng, Y. Lu, Y. Zhang, Y. Liu, J. Xu, W. Chen, Opt. Lett. 25 (2000) 1101.
[6] J. Dong, P. Deng, J. Xu, J. Cryst. Growth 203 (1999) 163.
[7] J. Dong, P. Deng, J. Lumin. 104 (2003) 151.
[8] J. Dong, P. Deng, Y. Liu, Y. Zhang, G. Huang, F. Gan, Chinese Phys. Lett. 19 (2002) 342.
[9] Y. Zhou, Q. Thai, Y.C. Chen, S. Zhou, Opt. Commun. 219 (2003) 365.
[10] E.A. Viktorov, D.R. Klemer, M.A. Karim, Opt. Commun. 113 (1995) 441.
[11] M.A. Larotonda, A.M. Yacomotti, O.E. Martinez, Opt. Commun. 169 (1999) 149.
[12] D. Pieroux, P. Mandel, K. Otsuka, Opt. Commun. 108 (1994) 273.
[13] E.A. Viktorov, P. Mandel, Opt. Lett. 22 (1997) 1568.
[14] R. Feldman, Y. Shimony, Z. Burshtein, Opt. Mater. 24 (2003) 393.
[15] J. Dong, M. Bass, Y. Mao, P. Deng, F. Gan, J. Opt. Soc., Am. B 20 (2003) 1975.
[16] S. Zhao, A. Rapaport, J. Dong, B. Chen, P. Deng, M. Bass, Opt. Mater. 27 (2005) 1329.
[17] T. Shoji, S. Tokita, J. Kawanaka, M. Fujita, Y. Izawa, Jpn. J. Appl. Phys. 43 (2004) L496.
[18] D.J. Ripin, J.R. Ochoa, R.L. Aggarwal, T.Y. Fan, Opt. Lett. 29 (2004) 2154.
[19] W. Kochner, Solid State Laser Engineering, Springer-Verlag, Berlin, Germany, 1999.
[20] A.G. Okhrimchuk, A.V. Shestakov, Phys. Rev. B 61 (2000) 988.
[21] E. Lacot, F. Stoeckel, J. Opt. Soc., Am. B 13 (1996) 2034.