Green Output of 1.5 W from a Diode-Pumped Intracavity Frequency-Doubled Self-Q-Switched and Mode-Locked Cr,Nd:YAG Laser

2007 Chinese Phys. Lett. 24 3149

(http://iopscience.iop.org/0256-307X/24/11/036)

Green Output of 1.5 W from a Diode-Pumped Intracavity Frequency-Doubled Self-Q-Switched and Mode-Locked Cr,Nd:YAG Laser *

DU Shi-Feng(杜仕峰)[1**], WANG Su-Mei(王素梅)[1], ZHANG Dong-Xiang(张东香)[1], LI De-Hua(李德华)[1], ZHANG Zhi-Guo (张治国)[1], FENG Bao-Hua(冯宝华)[1], ZHANG Shi-Wen(张世文)[2]

[1]*Laboratory of Optical Physics, Chinese Academy of Sciences, Beijing 100080*

[2]*North China Research Institute of Electro-Optics, Beijing 100015*

(Received 19 July 2007)

We report a diode-pumped intracavity frequency-doubled self-Q-switched and mode-locked Cr,Nd:YAG/KTP green laser with a Z-type cavity, which produces 1.5 W of average power at 532 nm with incident pump power 14.2 W. The individual mode-locked green pulse duration is about 560 ps with 149 MHz repetition rate. Almost 100% modulation depth of the mode-locked green pulses is achieved at an incident pump power of 4.13 W. The maximum energy of Q-switched green pulse is 19.8 μJ. The experimental results of pulse duration and pulse energy of Q-switched green pulse agree well with the theoretical calculations.

PACS: 42. 55. Xi, 42. 60. Fc, 42. 65. Ky

Simultaneously Q-switched and mode-locked intracavity frequency-doubled lasers, which can emit stable green laser with high repetition rate, high peak power and moderate average power, have attracted much attention for their wide applications in projection display, under-water communication, and medicine. Intracavity second-harmonic generation in the simultaneous Q-switched and mode-locked Nd^{3+}-doped lasers operating at fundamental wave of 1064 nm is a popular approach for obtaining such laser sources.[1−4] Cr^{4+}:YAG and semiconductor saturable absorber are often used to perform passive Q-switched and passive mode-locked.[5,6] In comparison with other saturable absorbers, the virtues of excellent optical properties, including good photochemical and thermal stability, low saturation intensity and high damage threshold, make Cr^{4+}:YAG widely used as a saturable absorber in passively Q-switched and mode-locked lasers. In addition, when YAG host crystals are codoped with Cr^{4+} and Nd^{3+}, the gain medium and the saturable absorber are combined in a single crystal, leading to much more simple and compact laser operation.[7] The self-Q-switched and mode-locked Cr,Nd:YAG laser has been experimentally demonstrated by Yang *et al.*[8] Their experimental results showed that the saturation intensity of Cr,Nd:YAG crystal for Q-switched and mode-locked operation is much smaller than that of Cr^{4+}:YAG crystal. Recently, a few researchers have reported the studies on this type crystal in green laser operation by using different cavities.[9−11] In comparison, multi-mirror folded cavities are suitable to realize simultaneously Q-switched and mode-locked intracavity frequency-doubled green lasers. Yang *et al.*[11] have reported a 132-mW output from a diode-pumped self-Q-switched and mode-locked green laser with a V-type cavity. In this Letter, we report a diode-pumped intracavity frequency-doubled self-Q-switched and mode-locked Cr,Nd:YAG/KTP green laser with a Z-type cavity. At an incident pump power of 14.2 W, the maximum average green output of 1.5 W is achieved with an optical conversion efficiency of 10.6% from the diode laser at 808 nm to the green output at 532 nm. To the best of our knowledge, this is the highest power achieved in green laser using this type crystal. The experimental results of pulse duration and pulse energy of Q-switched green pulse agree well with the theoretical calculations.

The experimental setup is shown schematically in Fig. 1. A Z-type cavity is designed to obtain good mode matching between the cavity-mode and the pump beam and to provide a proper spot size in the nonlinear crystal. The pump light at 808 nm from a fibre-coupled diode laser is focused into the Cr,Nd:YAG crystal by a coupling system. The focused beam in the laser medium has a diameter of 240 μm. A $\phi 5.5 \times 8$ mm Cr,Nd:YAG crystal is used in our experiment. The absorption coefficient of the crystal is $0.149\,\mathrm{cm}^{-1}$ at 1064 nm. The Cr,Nd:YAG crystal is cooled by water and the temperature of water is set at $12 \pm 0.1^\circ$C. The pump facet of Cr,Nd:YAG crystal is coated for high reflection at 1064 nm ($R > 99.9\%$) and high transmission at 808 nm ($T > 95\%$), and the other side is coated for antireflection at 1064 nm. A KTP crystal is cut for type-II phase matching at 1064 nm and coated for antireflection at 1064 nm and 532 nm on both the end faces. The folded concave mirror M_1 ($r = 30$ cm) and M_3 ($r = 5$ cm) are coated for high reflection at 1064 nm and 532 nm, while M_2 ($r = 22$ cm) is coated for high reflection at 1064 nm and high transmission at 532 nm. The distances between M_1 and

* Supported by the National Natural Science Foundation of China under Grant Nos 60278024 and 60438020.
** Email: sfdu@aphy.iphy.ac.cn

M_2, M_2 and M_3 are about 660 mm and 162 mm, respectively. The total cavity length is approximately 1 m. The temporal profile of the green laser pulses is recorded by a fast photodiode with a rising time of 350 ps and a digital oscilloscope (Tektronix 3052B, 500 MHz bandwidth). The average output power is measured with a laser powermeter.

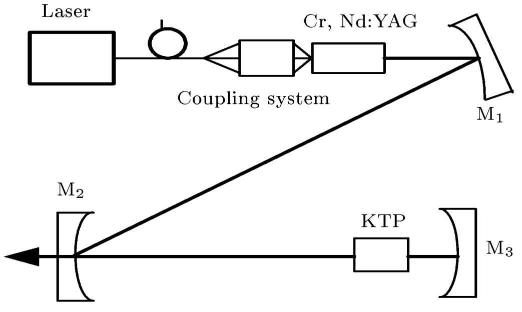

Fig. 1. Schematic of diode-pumped intracavity frequency-doubled Cr,Nd:YAG laser.

The threshold pump power for Q-switching and mode-locking of the Cr,Nd:YAG/KTP green laser is 0.63 W. Thus the saturation intensity is extraordinarily low. Figure 2 shows the variation of the average output power and repetition rate of the Q-switched green laser with the incident pump power. The average output power increases almost linearly with the increasing incident pump power. The repetition rate, which is limited by the recovery time from bleaching of the saturable absorber, increases fast first and then slow with the increasing incident pump power. At an incident pump power of 14.2 W, a maximum output power of 1.5 W at 532 nm is achieved with optical conversion efficiency of 10.6% from the diode laser at 808 nm to the green output at 532 nm. The corresponding pulse duration and pulse repetition rate of Q-switched envelope are 282.3 ns and 75.2 kHz, respectively. Figure 3 shows the dependence of the energy of Q-switched green pulses on the incident pump power, which is determined from the average output power and the repetition of Q-switched green pulse. The maximum pulse energy is 19.8 μJ at an incident pump power of 14.2 W. When the incident pump power exceeds the threshold power, almost 100% modulation depth of the mode-locked green pulses can be observed. A typical expanded temporal profile of a single Q-switched green pulse is shown in Fig. 4, while the train of the mode-locked pulses is shown in the insert of Fig. 4, which is recorded at an incident pump power of 4.13 W. It can be seen from Fig. 4 that the Q-switched pulse width is about 302.5 ns. The mode-locked pulse interval is 6.67 ns, corresponding to a repetition rate of 149 MHz, which matches closely with the cavity round-trip transit time. The mode-locked pulse duration of the green laser beam is measured using a digital oscilloscope (Tektronix TDS7254B, 2.5 GHz bandwidth) and a fast photodiode (Rising time $\sim$ 0.1 ns) and is found to be 560 ps.

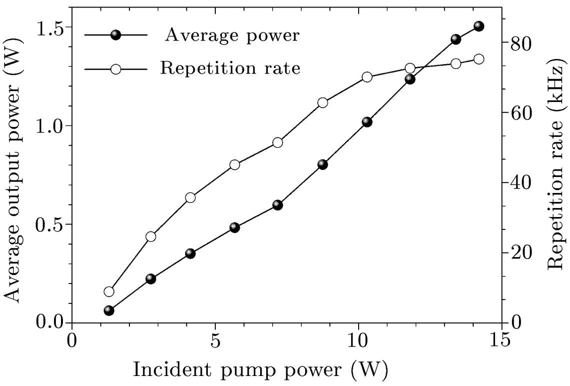

Fig. 2. Variation of the average output power and repetition rate of the Q-switched green pulse with the incident pump power.

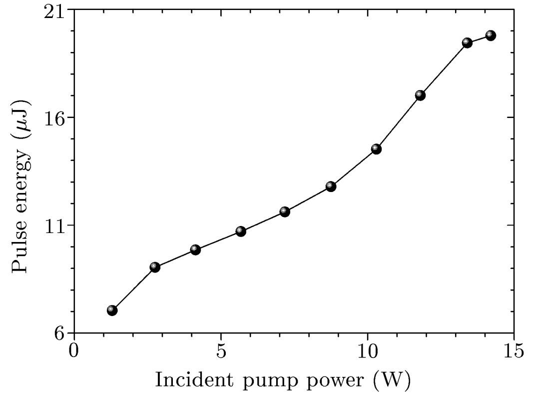

Fig. 3. Dependence of the pulse energy of the Q-switched green pulse on the incident pump power.

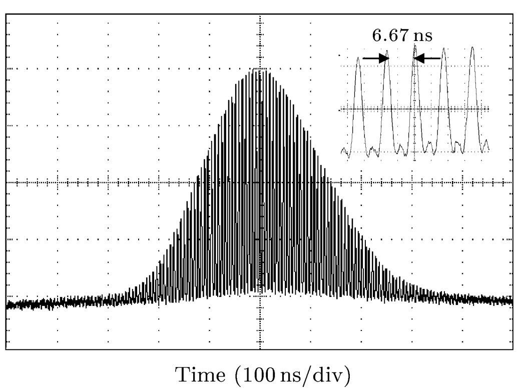

Fig. 4. Oscilloscope traces for the expanded temporal profile of Q-switched green pulse at an incident pump power of 4.13 W.

By according to the fluctuation mechanism, using the hyperbolic secant square function and regarding the second-harmonic conversion as the nonlinear loss of the fundamental wave, Mukhopadhyay *et al.*[3] have developed an analytical method for modelling the temporal pulse profiles of an intracavity frequency-doubled passively Q-switched and mode-locked Nd:YVO_4/KTP green laser. The temporal profile of Q-switched green pulse that leaks out from our system can be described as[3]

$$p_{2\omega}(t)=\Big(\frac{hv}{\sigma\tau_p}\Big)^2\frac{A^2}{A_N}\frac{\pi^2L_c^2d_{\rm eff}^2}{\varepsilon_0cn^{2\omega}n_1^\omega n_2^\omega\lambda_L^2}\cdot\frac{\sin^2(L_c\Delta k/2)}{(L_c\Delta k/2)^2}\sum_{m=0}^{\infty}\Phi_m^2{\rm sech}^4\Big(\frac{t-t_m}{\tau_p}\Big), \tag{1}$$

where hv is the fundamental laser photon energy, σ is the simulated emission cross section of the gain medium, the parameter τ_p is related to the mode-locked pulse duration τ of fundamental wave by $\tau=1.76\tau_p$,[12] A and A_N are the effective fundamental beam areas in the gain medium and the nonlinear crystal, respectively; L_c is the length of the nonlinear crystal, $d_{\rm eff}$ is the effective nonlinear coefficient of the nonlinear crystal, ε_0 is the permittivity of free space, c is the speed of light in vacuum, λ_L is the fundamental wavelength; $n^{2\omega}$, n_1^ω and n_2^ω are the harmonic and fundamental wave refractive indices, $t_m=mt_r$ (t_r is the cavity roundtrip time), and Δk is the phase mismatch. The relative amplitude Φ_m of the mode-locked pulse at the mth round trip is described as

$$\Phi_m=\Phi_{m-1}\exp\Big\{\Big[\exp\Big(-\gamma\sum_{k=0}^{m-1}\Phi_k\Big)-1\Big]\cdot[\ln(1/R)+L]+\Big[\exp\Big(-\gamma\sum_{k=0}^{m-1}\Phi_k\Big)-\Big[\beta+(1-\beta)\exp\Big(-\alpha\gamma\sum_{k=0}^{m-1}\Phi_k\Big)\Big]\Big]\cdot\ln(1/T_0^2)-\sigma_{NL}\Phi_{m-1}\Big\}, \tag{2}$$

where γ is the inversion reduction factor, R is the reflectivity of the M_2 mirror for the fundamental wave, L is the non-saturable intra-cavity roundtrip dissipative optical loss, and T_0 is the initial transmission of saturable absorber; $\beta=\sigma_{es}/\sigma_{gs}$ with σ_{gs} and σ_{es} being the ground state absorption cross section and the excited state absorption cross section in the saturable absorber; $\alpha=\sigma_{gs}A/\gamma\sigma A_s$ with A_s being the effective fundamental beam area in the saturable absorber, and σ_{NL} value is given by

$$\sigma_{NL}=\frac{4\pi^2L_c^2d_{\rm eff}^2}{3\varepsilon_0cn^{2\omega}n_1^\omega n_2^\omega\lambda_L^2}\frac{Ahv}{A_n\sigma\tau_p}\frac{\sin^2(L_c\Delta k/2)}{(L_c\Delta k/2)^2}. \tag{3}$$

By integrating Eq. (1) over time from zero to infinity, the output energy of second-harmonic Q-switched pulses can be obtained to be

$$E_{2\omega}=\frac{4A^2}{3A_N\tau_p}\Big(\frac{hv}{\sigma}\Big)^2\frac{\pi^2L_c^2d_{\rm eff}^2}{\varepsilon_0cn^{2\omega}n_1^\omega n_2^\omega\lambda_L^2}\cdot\frac{\sin^2(L_c\Delta k/2)}{(L_c\Delta k/2)^2}\sum_{m=0}^{\infty}\Phi_m^2. \tag{4}$$

Table 1. Parameters used in our calculation, most of them are taken from Refs. [3,14,15].

Parameters	Values	Parameters	Values
σ	6.5×10^{-19} cm^2	R	0.995
σ_{gs}	70×10^{-19} cm^2	n_1^ω	1.86
$d_{\rm eff}$	3.66×10^{-12} m/V	n_2^ω	1.746
ε_0	8.855×10^{-12} C^2/Nm^2	$n^{2\omega}$	1.79
β	0.28	L	0.01
γ	1.0	L_c	10 mm
Φ_0	1×10^{-3}	A/A_s	1

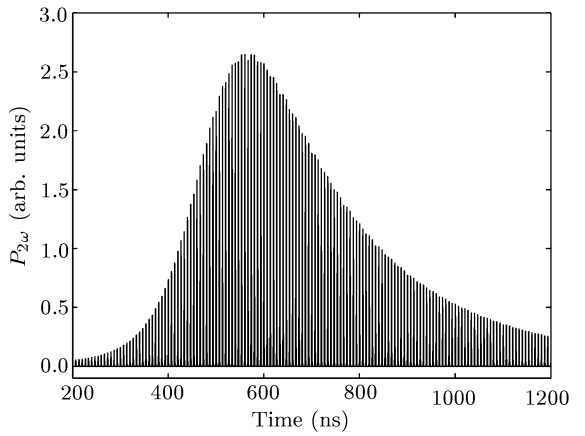

Fig. 5. Calculated result for the temporal profile of Q-switched green pulse at an incident pump power of 4.13 W.

The spot radii of the cavity mode in the laser medium and the KTP crystal are calculated by the ABCD matrix. Taking the thermal-lensing effect into account at the pump power of 4.13 W, the spot radii are found to be around 130 μm and 106 μm. Figure 5 shows the reconstructed temporal profile of Q-switched green pulse when using the parameters in Table 1 and Eq. (1). It can be seen from Fig. 5 that the duration of the Q-switched green pulse profile is about 321 ns, which is close to the experimental result of 302.5 ns shown in Fig. 4. It can be seen from Eq. (4) that the Q-switched green pulse energy depends on τ_p. In Fig. 6, we show how the Q-switched green pulse energy depends on τ_p at an incident pump power of 4.13 W. The pulse duration of the single mode-locked pulse at the second-harmonic is measured to be around 560 ps, and the duration for the mode-locked pulse at the fundamental wave is about $2^{1/2}$ times of that for the second-harmonic.[3,11] Hence the value of τ_p can be estimated to be $2^{1/2}\times560/1.76\approx450$ ps, and it is clear that the calculated pulse energy of Q-switched green pulse is 10.23 μJ, as shown in Fig. 6, which agrees well with the measured pulse energy of 9.86 μJ shown in Fig. 3. In our experiment, the decrease of the cavity-mode beam area in the laser medium with the increasing incident pump power is slower than that in the KTP crystal, leading to the increase of the Q-switched green pulse energy with the increasing incident pump power.

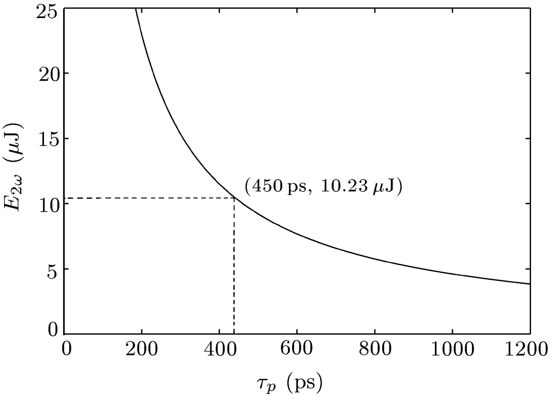

Fig. 6. Calculated dependence of pulse energy of Q-switched green pulse on τ_p at an incident pump power of 4.13 W.

In summary, we have presented a diode-pumped high average power self-Q-switched and mode-locked Cr,Nd:YAG/KTP green laser. The maximum average green power of 1.5 W is achieved at an incident pump power of 14.2 W with optical conversion efficiency of 10.6%. The modulation depth of the mode-locked green pulses is almost 100% at any incident pump power over the threshold power. The pulse duration of the mode-locked green pulse is 560 ps with 149 MHz repetition rate. The experimental results of pulse duration and pulse energy of Q-switched green pulse agree well with the theoretical calculations.

References

[1] Wang J Y, Zheng Q, Xue Q H and Tan H M 2003 *Chin. Opt. Lett.* **1** 604
[2] Mukhopadhyay P K, Alsous M B, Ranganathan K, Sharma S K, Gupta P K, George J and Nathan T P S 2003 *Opt. Commun.* **222** 399
[3] Mukhopadhyay P K, Alsous M B, Ranganathan K, Sharma S K, Gupta P K, George J and Nathan T P S 2004 *Appl. Phys.* B **79** 713
[4] Yang K J, Zhao S Z, Li G Q, Li M, Li D C, Wang J and An J 2006 *IEEE J. Quantum Electron.* **42** 683
[5] Chen Y F, Lee J L, Hsieh H D and Tsai S W 2002 *IEEE J. Quantum Electron.* **38** 312
[6] Zhang S J, Wu E, Pan H F and Zeng H P 2004 *IEEE J. Quantum Electron.* **40** 505
[7] Li S Q, Zhou S H, Wang P, Chen Y C and Lee K K 1993 *Opt. Lett.* **18** 203
[8] Yang L, Feng B H, Zhang Z G, Gaebler V, Liu B N, Hans J E and Zhang S W 2002 *Chin. Phys. Lett.* **19** 1450
[9] Yu T, Cui J W, Lu Y T and Hu Q Q 2001 *Chin. J. Lasers* B **10** 321
[10] Du S F, Wang S M, Zhang D X, Feng B H, Zhang C Y, Zhang L, Zhang Z G and Zhang S W 2006 *Chin. Phys.* **15** 1522
[11] Yang K J, Zhao S Z, Li M, Li G Q, Li D C, Wang J and An J 2007 *J. Appl. Phys.* **101** 013105
[12] Siegman A E 1986 *Lasers* (Mill Valley, CA: University Science Books) p 1122
[13] Degan J J 1995 *IEEE J. Quantum Electron.* **31** 1890
[14] Koechner W 1996 *Solid State Laser Engineering* 4th edn (Berlin: Springer) p 49
[15] Burshtein Z, Blau P, Kalisky Y, Shimony Y and Kikta M R 1998 *IEEE J. Quantum Electron.* **34** 292