Dual-loss-modulated Q-switched and mode-locked YVO_4/Nd:YVO_4/KTP green laser with EO and Cr^{4+}:YAG saturable absorber

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Abstract: By simultaneously employing the electro-optic (EO) modulator and Cr^{4+}:YAG saturable absorber, a diode-pumped dual-loss-modulated Q-switched and mode-locked (QML) YVO_4/NdYVO_4/KTP green laser is presented. In comparison with the singly passively QML green laser with Cr^{4+}:YAG, the dual-loss-modulated QML green laser with EO and Cr^{4+}:YAG can generate more stable pulse train with deeper modulation depth, shorter pulse width, greater pulse energy and higher peak power. For the dual-loss-modulated QML green laser, at a pump power of 18 W and a repetition rate of 1 kHz, the pulse width and the pulse energy of the Q-switch envelope as well as the peak power of QML green laser are 42.1 ns, 360 μJ and 382 kW, respectively, corresponding to the pulse width compression 62%, the pulse energy improvement 10 times and the QML peak power increase 40 times when compared with that of the singly passively QML green laser.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3515) Lasers, frequency doubled ; Lasers, pulsed (140.3538) .

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1. Introduction

Intracavity frequency-doubled green lasers with ultra-short pulse duration and high peak power have been widely applied in the fields of laser medicine, information storage, chemical processing, and coherent telecommunications. This kind of laser can be easily obtained by inserting a nonlinear crystal into a simultaneously passively Q-switched and mode-locked (QML) solid-state laser with Cr^{4+}:YAG or semiconductor saturable absorber at the fundamental wave length of 1.06 μm [1–8]. Because the singly passively QML green lasers have a poor shot-to-shot stability and a low controllability for the pulse repetition rate as well as can hardly reach the mode-locked modulation depth of 100% in Q-switched pulse envelope [1,2,4–6], their applications are limited very much. Continuous-wave mode-locked lasers can improve the average output power stability by bringing all longitudinal modes into phase with one another [9,10], and the intracavity frequency-doubled generation in the diode-pumped actively or passively mode-locked lasers have been demonstrated [11]. However, in these lasers the energy per pulse is low due to the continuous wave mode-locking, further more, their repetition rate are ultimately determined by the cavity length, cannot be controlled optionally. Generation of the stable QML pulses with the higher energy and the optional repetition rate can be obtained by the integrations of the active acousto-optic modulator and the passive saturable absorption in the doubly QML lasers [12–14]. In those dual-loss-modulated lasers, the repetition rate of the Q-switched envelope is controlled by the active modulator while the mode-locked pulses depend on both the actively modulated loss and the saturable absorption. Introduction of an active modulator changes the QML characteristics dramatically. The active loss modulation reduces the inherent statistical nature of the early stage pulse buildup, while retaining the effect of the saturable absorber as nonlinear loss element and Q-switch for final stage pulse shortening. The statistical noise pulse which is going to be the mode-locked pulse is tailored by active modulator for each laser shot, giving an improved shot-to-shot stability for the pulsed energy. The experimental results show that the dual-loss-modulated QML 1.06 μm-lasers with the active acousto-optic modulator and the passive saturable absorption can generate more stable pulses with higher peak power than that of the singly passively QML 1.06 μm lasers with the saturable absorber. In comparison to the acousto-optic modulator, the electro-optic modulator is known to be advantageous in its faster switching and better hold-off ability. However, the simultaneously Q-switched and mode-locked intracavity-frequency-doubled green lasers with the active electro-optic modulator and the passive saturable absorption haven't been reported as far as we known.

In this paper, by simultaneously employing EO modulator and Cr^{4+}:YAG saturable absorber, a diode-pumped dual-loss-modulated QML $YVO_4/NdYVO_4$/KTP green laser is demonstrated. The experimental results show that the dual-loss-modulated QML green laser can generate more stable pulse with deeper mode-locked modulation, shorter pulse width, greater pulse energy and higher peak power when compared with the singly passively QML green laser with Cr^{4+}:YAG.

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2. Experimental setup

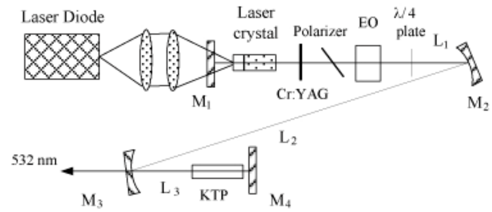

Fig. 1. Experimental setup of QML YVO_4/Nd:YVO_4/KTP green laser with EO and Cr^{4+}:YAG

The experimental setup is shown in Fig. 1. The laser host is an a-cut YVO_4/Nd:YVO_4 composite crystal which is fabricated by the thermal diffusion bonding technique with a dimensions of 3×3×(3+8) mm^3. The Nd:YVO_4 in composite crystal has a Nd^{3+} doping concentration of 0.5 at.%. One end facet of the Nd:YVO_4 crystal is antireflective (AR) coated at 1064 nm, while the other end facet of YVO_4 is AR coated at 808 nm and 1064 nm acting as the pump end. The frequency doubling crystal, KTP, with the dimension of (3×3×5 mm^3) is cut for type—IIphase matching at 1064 nm (θ=90 °C,φ=23.2 °C) and is AR coated at 1064 nm and 532 nm. In order to efficiently dissipate the heat deposition, the laser crystal and KTP are wrapped with a thin layer of indium foil and fitted into a copper holder cooled by a thermo-electric cooler. The pump source used is a fiber-coupled diode laser emitting at 808 nm with the maximum output power of 30 W (FAP system, Coherent, Inc.). The core size of the fiber is 400 μm in radius, with a numerical aperture of 0.22. The folded laser cavity consists of four mirrors. Flat mirror M_1 AR coated at 808 nm and high-reflection (HR) coated at 1064 nm is placed near laser crystal . Concave mirror M_2 with the radius of curvature (ROC) of 500 mm is HR coated at 1064 nm, acting as one resonator mirror. The green output mirror M_3 with the ROC of 150 mm is HR coated at 1064 nm and AR at 532 nm. Flat mirror M_4 is HR coated at both 1064 and 532 nm. The EO modulator (BBO crystal, the repetition rate 1 kHz-5 kHz) with a polarizer and λ/4 plate is used as active Q-switch modulation while a Cr^{4+}:YAG wafer with small signal transmission of 70% is used as passive saturable absorber. The lengths of the three arms, L_1, L_2 and L_3 are chosen to be 570, 740 and 115 mm, respectively, corresponding to a total cavity length of approximately 142.5 cm. Using the well-known ABCD matrix method, we have simulated the radii of the TEM_{00} mode with the values of 300-400 μm in laser crystal and Cr^{4+}:YAG saturable absorber. A MAX 500AD laser power meter (Coherent, Inc., USA) is used to measure the generated green laser power. The pulsed temporal behavior of green laser is recorded by a fast photo-electronic diode (with response time of less than 1 ns) and a TDS620B digital oscilloscope (Tektronix, Inc., USA) that has a 500 MHz bandwidth and a 2.5 Gs/s sample rate.

3. Experimental results

When the EO modulator is removed from the cavity, the laser is the singly passively QML green laser with Cr^{4+}:YAG. When the EO modulator is inserted into the cavity, the laser is the dual-loss-modulated QML green laser with EO and Cr^{4+}:YAG. For the singly passively QML green laser, the repetition rate of the Q-switched envelope depends on the pump power and varies from 5 kHz to 32 kHz when the pump power increases from 3 W to 18 W. For the dual-loss-modulated QML green laser, the repetition rate of the Q-switch envelope is equal to the repetition rate of EO modulator and more stable than that of the singly passively QML green laser.

Figure 2 shows the average output power versus the pump power for the singly passively and dual-loss-modulated QML green lasers. From Fig. 2, we can see that the threshold powers for two QML green lasers are 3 W and 4 W, respectively, in which the higher threshold power for the dual-loss-modulated QML green laser is induced by the additional loss of the inserted EO switch. Because the singly passively QML green laser has the higher repetition rate, its average output power is higher than that of the dual-loss-modulated QML green laser. At the

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pump power of 18 W, a maximum output power of 1.13 W with the optical conversion efficiency of 6.3% is obtained for the singly passively QML green laser, while the maximum output power of 0.77 W with the optical conversion efficiency of 4.2% is obtained for the dual-loss-modulated QML green laser at 5 kHz.

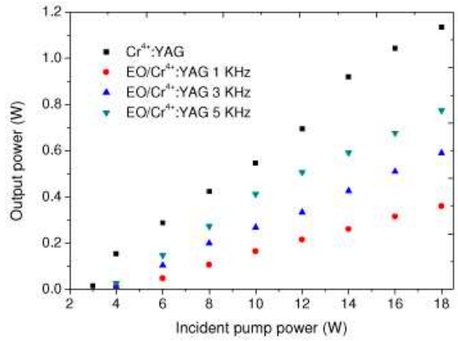

Fig. 2. Average output power versus incident pump power for various EO frequencies.

Two QML green laser pulse trains in longer time scale at the incident pump power of 10 W are recorded by the oscilloscope and shown in Fig. 3. The pulse to pulse amplitude fluctuation in the singly passively QML green laser easily exceeds 40%, while in the dual-loss-modulated QML green laser it is relatively stable with the value of 4.8%. In Nd:YVO_4 QML laser using Cr^{4+}:YAG at the fundamental wavelength, the ratio of the mode area at the gain medium (A) to that at the saturable absorber (A_s), that is A/A_s , must reach 20-30 to saturate the excited state absorption (ESA) at the Cr^{4+}:YAG crystal [15], this value will be even large in frequency doubled laser [7]. In our experiment, In order to prevent Cr^{4+}:YAG from being damaged at high pump power, we put it closely to YVO_4/Nd:YVO_4 crystal where the ratio of A/A_s is approximately to 1. In a purely passively Q-switched laser, this ratio cannot satisfied the saturable intensity for the ESA, so the output QML pulse is unstable and the modulation depth cannot reach to 100%, seen in Fig. 3 and Fig. 4. In the double Q-switching, however, the intracavity intensity is increased significantly due to the insertion of the EO Q-switch. The absorption of the Cr^{4+}:YAG wafer will be saturated immediately when the EO Q-switch is "on" because of the large population inversion in laser medium, inducing a stable pulse train with 100% modulation depth.

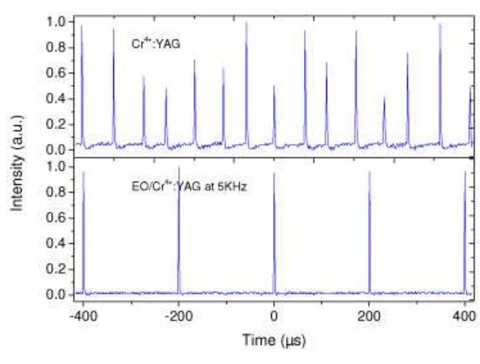

Fig. 3. Oscilloscope traces of the pulse trains for two QML green lasers. Upper part: Cr^{4+}:YAG single QML laser, lower part: EO/Cr^{4+}:YAG doubly QML laser.

The temporal shape of the Q-switched pulse envelope at the pump power of 18 W is shown in Fig. 4. It can be seen that the dual-loss-modulated QML green laser pulse has the 100% modulation depth, whereas it is just about 90% in the singly passively QML green laser. Meanwhile we can also see that the pulse width of the Q-switched envelope is 111.2 ns

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for singly passively QML green laser and 42.1 ns for the dual-loss-modulated QML green laser, respectively, corresponding to a pulse width compression 62%.

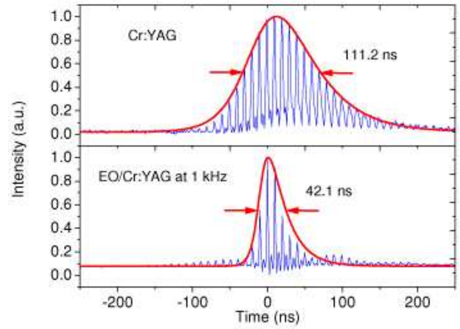

Fig. 4. Oscilloscope profiles of the Q-switched pulse envelope for two QML green lasers at the pump power of 18 W. Upper part: Cr^{4+}:YAG single QML pulse, lower part: EO/Cr^{4+}:YAG doubly QML pulse.

The expanded oscilloscope traces of the mode-locked pulses train are showed in Fig. 5, from which we obtain that the mode-locked pulses within the Q-switched envelope are separated by 9.8 ns, which matches exactly with the cavity round-trip transmit time and corresponds to a repetition rate of 102 MHz. The average rise time of the mode-locked pulse in the two QML lasers are 1.3 ns and 1.23 ns, respectively.

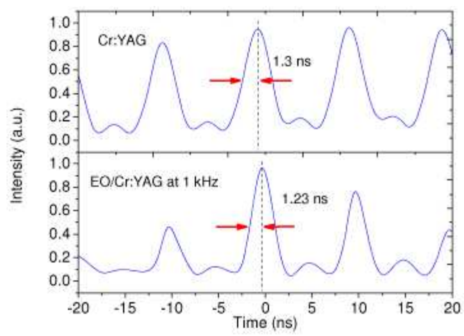

Fig. 5. Expanded oscilloscope traces of the trains for two QML green lasers at the pump power of 18 W. Upper part: Cr^{4+}:YAG single QML pulse, lower part: EO/Cr^{4+}:YAG doubly QML pulse.

Figure 6 gives the pulse width of the Q-switched envelope versus the pump power for the two kinds of lasers. It can be seen that the pulse width always decreases with the increase of the incident pump power and is obviously compressed in the dual-loss-modulated QML green laser when compared with that in the singly passively QML green laser.

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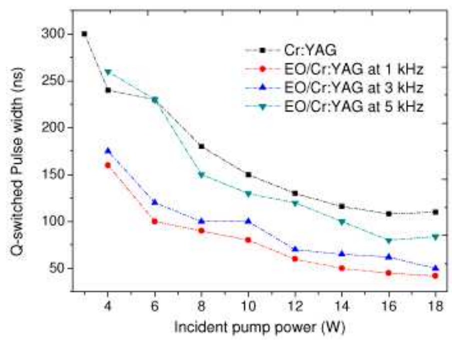

Fig. 6. Pulse width of the Q-switched envelope versus the incident pump power.

According to the repetition rate and the pulse width of the Q-switched envelope, the pulse energy of the single Q-switched envelope can be calculated. Figure 7 shows the pulse energy of the Q-switched envelope versus the incident pump power for two kinds of QML lasers. From Fig. 7, we can see that the pulse energy of the Q-switched envelope almost increases lineally with pump power and is much higher in the dual-loss-modulated QML green laser than in the singly passively QML green laser. At the pump power of 18 W, the obtained maximum pulse energies are 35 μJ for the singly passively QML green laser and 360 μJ for the dual-loss-modulated QML green laser at 1 kHz, respectively, corresponding to a 10 times pulse energy improvement.

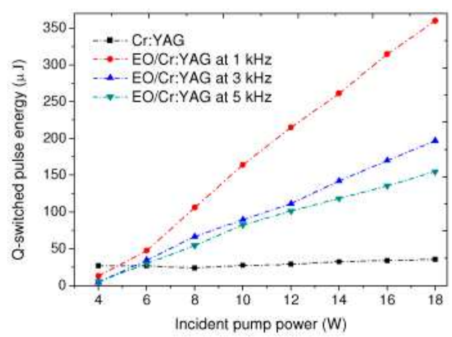

Fig. 7. Pulse energy of the Q-switched envelope versus the incident pump power.

Because the mode-locked pulses within the Q-switched envelope are separated by the cavity roundtrip transmit time, according to the pulse width of the Q-switched envelope, the number of the mode-locked pulse can be calculated. Then based on the pulse energy of the Q-switched envelope, the average mode-locked pulse energy within the Q-switched envelope can be also calculated, which is shown in Fig. 8. It can be seen that at the pump power of 18 W and the repetition rate of 1 kHz, the average mode-locked pulse energy in the dual-loss-modulated QML green laser is about 72 microjoule which is much higher than that of 2.2 microjoule in the singly passively QML green laser.

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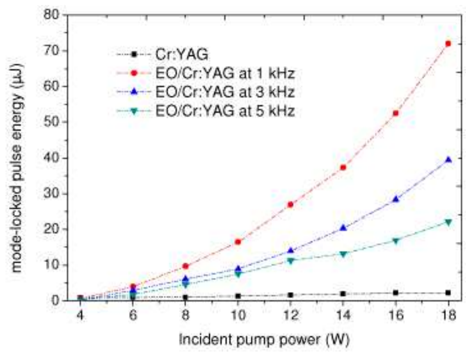

Fig. 8. Average mode-locked pulse energy versus the incident pump power.

The measured mode-locked pulse width is limited by the resolution of the detection devices used in the experiment. The measurement of mode-locked pulse-width using an autocorrelator has not been performed. According to the expanded oscilloscope traces of the mode-locked pulse within the Q-switched envelope, the mode-locked pulse width can be estimated by the formula [16]

$$t_{real} = \left(t_{measure}^2 - t_{probe}^2 - t_{oscilloscope}^2\right)^{1/2}, \quad (1)$$

here, t_{real} is the real time of the pulse, $t_{measure}$ is the measured rise time, t_{probe} is the rise time of the probe and $t_{oscilloscope}$ is the rise time of the oscilloscope. In our experiment, the average rise time of the mode-locked pulse in the singly passively and dual-loss-modulated QML laser are 1.3 ns and 1.23 ns, as shown in Fig. 5. The rise time of oscilloscope is 0.7 ns, and the rise time of the GaAs probe is about 1 ns. Assuming that the pulse width is approximately 1.25 time more than the rise time, the estimated mode-locked pulse widths for two QML green lasers are 235 ps and 188 ps, respectively. According to the pulse energy and the pulse width of the mode-locked pulse, the average mode-locked pulse peak power for two kinds of QML green lasers can be calculated, which is shown in Fig. 9. At the pump power of 18 W, the obtained maximum peak power are 9 kW for the singly passively QML green laser and 382 kW for the dual-loss-modulated QML green laser at 1 kHz, respectively, corresponding to a peak power increase 40 times.

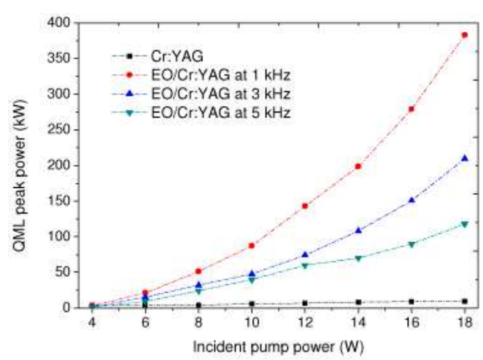

Fig. 9. Average mode-locked pulse peak power versus the incident pump power.

4. Conclusion

In conclusion, we have successfully realized a diode-pumped dual-loss-modulated QML YVO_4/Nd:YVO_4-KTP green laser by using both an EO modulator and a Cr:YAG saturable absorber. Under the pump power of 18 W, a peak power of 383 kW is obtained at the repetition rate of 1 kHz which is significantly improved with more than 40 time when compared with that of the single Cr^{4+}:YAG QML laser. The experimental results show that the dual-loss-modulated QML green laser with EO and Cr^{4+}:YAG can generate a more stable pulse train with the deeper modulation depth, the shorter pulse width, the greater pulse energy and the higher peak power in comparison with the singly passively QML green laser with Cr^{4+}:YAG.

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