Stable Q-switched mode-locked Nd^{3+}:$LuVO_4$ laser by Cr^{4+}:YAG crystal

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Abstract: In use of saturable Cr^{4+}:YAG crystals, we have demonstrated the stable Q-switched and mode-locked (QML) operation of the Nd:$LuVO_4$ laser. The operation range of QML in use of the Cr^{4+}:YAG is larger than that use of SESAM and NLM. The obtained shape of Q-switched envelope, repetition rate and pulse energy are demonstrated to depend on the initial transmittance of the Cr^{4+}:YAG and reflectivity of the output coupler. Using R = 60% and T_0 = 40%, the highest pulse energy of 77 μJ of each Q-switched envelope, and the highest peak power about 200 kW of Q-switched mode-locked pulses can be obtained at 15 W pump power. It demonstrate the superior characteristic of the Nd:$LuVO_4$ crystal.

OCIS codes: (140.4050) Mode locked laser; (140.3580) Lasers, solid state; (140.3480) Lasers, diode pumped; (190.0190) Nonlinear optics

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1. Introduction

High-peak power and short-pulse lasers are continuously interested in laser physicist because they have various practical applications. Generally, continuous wave mode-locking (CWML) is widely used technique in generating ultra short optical pulses. However, its repetition rate is restricted by the cavity length and is in tens of MHz. Due to these characteristics, the CW-ML pulses have various advantages such as such as wavelength conversion, supercontinuum generation [1], optical communication, optical switching, optical clocking, and nonlinear optical measurement. Nevertheless, high repletion rate pulses will accumulate heat in materials, leading to thermal lensing in optical nonlinearity measurements such as Z scan measurement. On the contrary, the Q-switched can generate lower repletion rates and higher pulse energies output. However, the generated Q-switched pulsewidth is comparative longer relative to the CW-ML pulses so that they have lower peak powers.

Simultaneously Q-switched and mode-locked (QML) lasers possess the superior property of high peak power over the CW mode-locked lasers but retain almost the same pulsewidth. The power of central ML peak pulse in the Q-switched envelope can be greatly enhanced and the repletion rate of pulses is greatly reduced. Especially for picosecond (ps) mode-locked laser, which may not have enough peak intensity for achieving efficient wavelength conversion and supercontinuum generation, the QML provides a solution for these problems. Some methods like cavity dumping and regenerative amplifier have similar effect but their configurations are more complicated than the QML system.

Recently, the QML pulses generated from diode-pumped solid-state lasers (DPSSL) have been widely reported because they possess several advantages, e.g., compactness, high reliability, high efficiency, and high output peak power. Neodymium-doped orthovanadate crystals have been one of the widely used gain media for DPSSL due to their high gain, superior thermal properties and chemical stability. The representative neodymium-doped orthovanadate crystal, Nd:YVO_4, has become an industrially and commercially used laser crystal in DPSSL. Other crystal, such as Nd:$GdVO_4$, is also widely reported to produce low threshold and high peak power pulses [2-4] due to its relatively high thermal conductivity [5]. Recently, Nd:$LuVO_4$ [6-7], a new member of the orthovanadate family, has been paid much attention as a promising candidate of excellent DPSSL crystal due to its high absorption and emission cross sections over other reported crystals.

With the semiconductor saturable absorber mirror (SESAM) or nonlinear mirror (NLM) technique [1-2], the QML pulses can be obtained prior to the complete CW mode-locking state while increasing the pump power. However, the pump power for stable QML operation with regular QML pulses is limited in a small range. By integrating the techniques of NLM and SESAM [8], the range of QML state can be extended to the higher pump power to generate regular stable high output power QML pulses with fixed period and Q-switched envelope.

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Generally, the Cr^{4+}:YAG crystal is an effective slow saturable absorber for Q-switching but not for mode-locking. However, the simultaneously Q-switching and mode locking had been observed due to the excite-state absorption (ESA) while the intracavity intensity is high enough [9]. With Cr^{4+}:YAG as saturable absorber, stable and high peak power QML pulses have been generated in Nd:YVO_4, Nd:$GdVO_4$, Nd:$Gd_{0.64}Y_{0.36}VO_4$ and Nd:YLF lasers [9-12]. In Nd:$LuVO_4$ laser, CW-mode locking has been demonstrated with a GaAs wafer [13] to generate short pulses; and with an acousto-optical modulator [14] and a Cr^{4+}:YAG as saturable absorber [15] Q-switching were also reported in Nd:$LuVO_4$ laser to produce high pulse energy. However, it is still lack of reports on simultaneously Q-switched and mode-locked Nd:$LuVO_4$ laser using a Cr:YAG saturable absorber.

In this paper, instead of using the plano-concave cavity [15], we use the z-type cavity resonator to achieve smaller cavity beam size for enhancing intracavity intensity inside Cr^{4+}:YAG. We successfully demonstrated low repetition rate and high peak power Q-switched and mode-locked pulses in diode-pumped a-cut Nd:$LuVO_4$ laser by the Cr^{4+}:YAG crystal. In use of the different permutation of the initial transmittance T_0 of the Cr^{4+}:YAG and the reflectance of the output coupler R, the output characteristics including the repetition rates, pulse energies and shape of the Q-switched envelopes will be investigated.

2. Experiments

The schematic setup of our laser with folded z-configuration is shown in Fig. 1. A fiber-coupled diode-array laser (FAP-81-16C-800-I, Coherent Inc.) with center wavelength of 809 nm was used as the pump source. The output beam from the fiber was imaged on the laser crystal, which is a 3x3x8 mm^3 a-cut Nd:$LuVO_4$ crystal (with 0.5-at.% Nd^{3+} concentration), through an 1:1.8 optical imaging accessory (OIA's, Coherent Inc.). One side of laser crystal (S_1) is high reflection (HR) coated at 1064 nm and anti-reflection (AR) coated at 808 nm as an end mirror of the resonator; while the other side (S_2) with 2 degree wedge is AR coated at 1064 nm. Two curved mirrors M_1 and M_2, with radii of curvatures of 500 and 200 mm, were used as folding mirrors to conduct cavity beam through a Cr^{4+} :YAG to the output coupler (OC). The distance between the gain medium and M1 is 30 cm, that from M1 to M2 is 80 cm and from M2 to OC is 13.5 cm. We put Cr^{4+} :YAG about 10.5 cm in front of the output coupler. We therefore can estimated the beam diameter at Cr^{4+} :YAG to be about 150 μm. We chose different combinations of OC with reflectivity of 60% and 80% at 1064 nm and Cr^{4+}:YAG saturable absorber with initial transmittance T_0 of 80%, 55% and 40% to optimize the generated QML pulses.

The output of the Nd:$LuVO_4$ laser from either OC or the wedged facet of the laser crystal was measured by a power meter (Ophir Inc.) or detected by a high speed InGaAs detector (Electro-Physics Technology, ET 3000) that was connected to the oscilloscope (LeCroy LT372, bandwidth 500 MHz) or an optical spectrum analyzer (Ando-AQ6315A) with resolution of 0.01 nm. A noncollinear autocorrelator containing a 2-mm thick type-I BBO was used to measure the width of mode-locked pulse.

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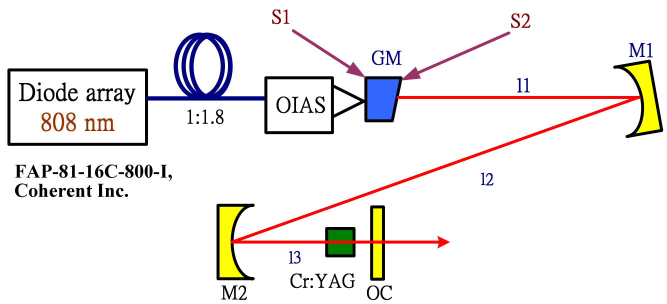

Fig. 1. Schematic diagram of diode-pumped Q-switched mode-locked $Nd:LuVO_4$ laser. GM is gain medium ($Nd:LuVO_4$), M_1 and M_2 are the folding mirrors and OC is the output coupler.

3. Results and discussion

The output powers versus pump power (P_p) at the CW states (black squares) and the QML states in use of T_0 = 80% ((blue diamonds), 55% (green triangles) and 40% (red circles) were shown in Fig. 2(a). As expected, the QML state can be operated provided that lasing threshold is achieved after the saturable absorbing Cr^{4+}:YAG crystal having been inserted into the laser cavity. Besides, the lasing threshold increases, the output power becomes lower as increasing the cavity loss via lowering R and T_0. With the same T_0, the output power using R = 80% [solid symbols] are generally higher than that of using R = 60% (open symbols). Although the non-saturable absorbing and even the thermal induced loss of the saturable absorber also influence the threshold, due to the cavity beam passing twice through the absorber and being reflected once by the OC in a round trip, more influence of the threshold and the output power on T_0 (dependence of T_0^2) than on R. In Fig. 2(a), we obtained the larger stable range of QML operation using Cr^{4+}:YAG than that in use of SESAM [1] or NLM [2], in which the QML state can usually be observed before entering completely CW-ML state as increasing the pump power but the operation range is very small. The QML state can only be observed as the pump powers increased from 1.7 W to 2.6 W for SESAM [1] and 2 W to 2.3W for NLM [2].

Similar effects of T_0 and R can be found in the repetition rates (R_{ep}) of the Q-switched envelope which were revealed in Fig. 2(b), the values show increase tendency as increasing the pump power. With the same T_0 and pump power, the value of R_{ep} for R = 80% is slightly higher than R = 60%. In use of R = 60%, the highest value of R_{ep} for T_0 = 80% is about 68 kHz that is relatively higher than the 23 kHz and 14 kHz as T_0 = 55%, and 40%, respectively.

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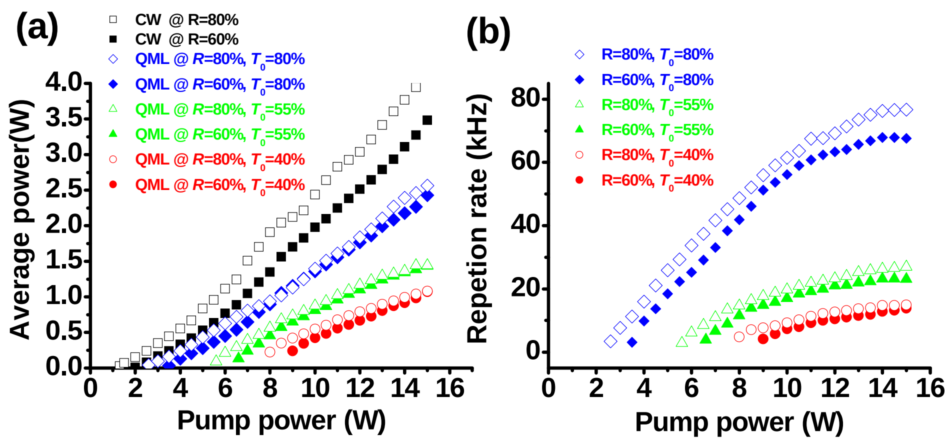

Fig. 2. (a). The average output powers, and (b) the repetition rates versus the pump power at the CW state (black squares) and QML states with the T_0=80% (blue diamonds), 55% (green triangles), and 40% (red circles).

The expanded Q-switching envelopes in use of the pump power of 13.5 W are shown in Fig. 3. Inside the envelope, a number of discrete and periodic mode-locking (ML) pulses with time interval about ~ 8 ns can obviously be seen. The width of the stable ML pulse was measured using an autocorrelator and shown in Fig. 4 (black squares) that reveals the pulsewidth t_0 about 56 ps by fitting to the Sech^2 shape (red curve). In this experiment, three different initial transmittance of Cr^{4+}:YAG, T_0 = 40%, 55%, and 80% as three columns in Fig. 3, were used to match with reflectance of OC, R = 60% and 80%, as two rows in Fig. 3. By fitting the envelopes with the formula

$$P(t) = \frac{a}{\{\exp[(1.76 * t / t_1] + \exp[-1.76 * t / t_2]\}^2}, \quad (1)$$

in which a is the scaling factor, we could obtain the rising time t_1 and the falling time t_2 of the Q-switched envelopes, respectively. Therefere, the widths and asymmetric factors of these Q-swithced envelopes can be estimated by the definition of $\tau = (t_1+t_2)/2$ and t_1/t_2. Together with the numbers of ML pulses (N) in each Q-switched envelopes, the energies of the highest ML pulses (E_{ML}), and the the calculated initial inversion (n_i) and the threshold inversion (n_t) for different R and T_0 were listed in Table I. These listed parameters can also be theoretically calculated using the model proposed by J. Liu et al. [16] if the laser parameters including the stimulated emission cross section of gain medium and the absorption cross section of saturable absorber are given.

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Table I

	T_0 = 40%		T_0 = 55%		T_0 = 80%	
***R*=**	**60%**	**80%**	**60%**	**80%**	**60%**	**80%**
NO. of pulses *N*	**7**	**11**	**9**	**13**	**16**	**22**
t_1 (ns)	**28**	**23**	**41**	**36**	**92**	**92**
t_2 (ns)	**83**	**157**	**104**	**166**	**162**	**267**
τ (ns)	**55**	**90**	**72**	**101**	**126**	**179**
t_1/t_2	**0.34**	**0.15**	**0.39**	**0.21**	**0.57**	**0.34**
E_{ML} (mJ)	**11**	**6.6**	**6.9**	**4.1**	**2.2**	**1.5**
n_i*10^{15} (mm)$^{-3}$	**10.1**	**8.89**	**7.39**	**6.16**	**4.18**	**2.95**
n_t*10^{15} (mm)$^{-3}$	**2.27**	**1.04**	**2.27**	**1.04**	**2.27**	**1.04**

Generally, t_1, t_2 and τ decreases as T_0 decreases, no matter what reflectance of OC were used. However, the rising time t_1 strongly depends upon T_0 but it has a little effect on change of R. In contrast, the falling time t_2 increases as both T_0 and R increase. It may be due to that the rising time t_1 is mainly determined by the initial inversion n_i, in which the initial spontaneously emitted photons (n_i) begin to experience positive net gain. The initial inversion is defined as

$$n_i = \frac{\ln(1/T_0^2) + \ln(1/R) + L}{2\sigma l}, \tag{2}$$

where L is nonsabturable intracavity round-trip optical loss, σ and l are the stimulated emission cross section and the length of gain medium. The larger initial emitted photons n_i, the faster is to extract energy stored in gain medium so as to bleach the saturable absorber and to reach the threshold inversion n_t with $T_0 \sim 1$. This results in the smaller t_1. Because n_i quadraticly depends on T_0 but only linearly on R in Eq. (2), the calculated n_i (also listed in Table I) using $\sigma = 1.46\text{x}10^{-18}\ \text{cm}^2$ for the used a-cut Nd:$LuVO_4$ crystal and L = 2% reveal consistent dependence of t_1. On the other hand, the falling time t_2 measures the decay time of cavity photons after the absorber being completely bleached, and therefore, is related to the photon lifetime according to

$$t_f \approx \frac{nl}{c(1-R)}, \tag{3}$$

Here, n is the index of the gain medium and c is the velocity of the light. Thus, the longer t_2 is expected for the larger R no matter what T_0 is used. Nevertheless, it is not the case in Fig. 3 and Table I, in which the laser with the lower T_0 experiences the shorter decay time t_2. The dependence of t_2 on T_0 could be due to temporal shaping via the recovered absorption of the absorber with lower T_0 or larger absorption which possesses the higher concentration of

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absorption ions to raise the cavity loss in the falling tail of the QML pulse.

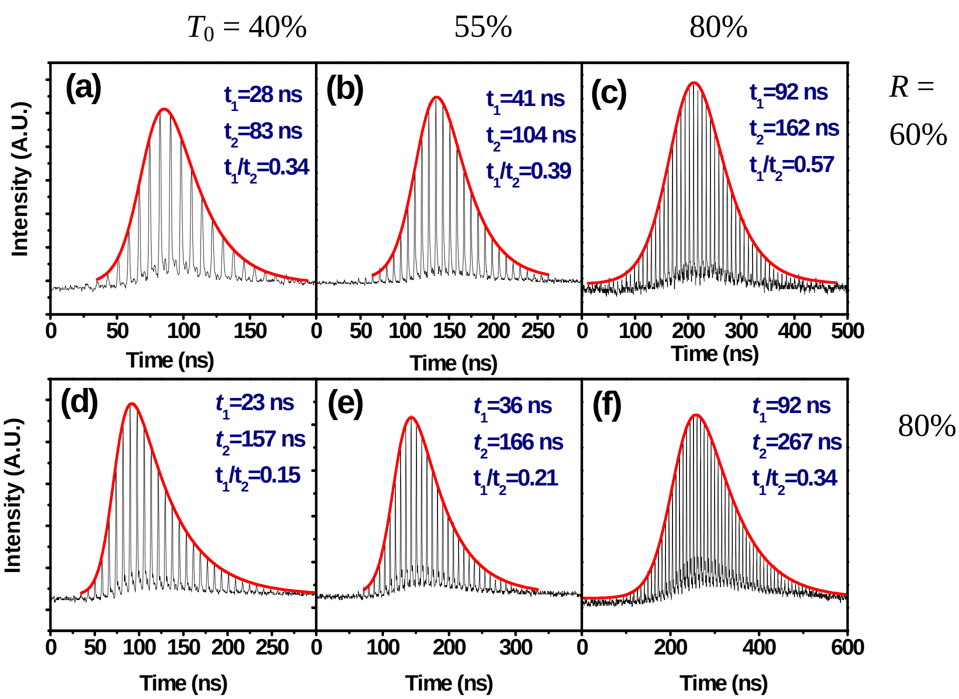

Fig. 3. Expanded temporal shape of a single Q-switched & mode-locked pulse trains at 13.5W pumping for R = 60% with T_0 =40% (a), 55% (b), and 80% (c); and R =80% with T_0 =40% (d), 55% (e), and 80% (f).

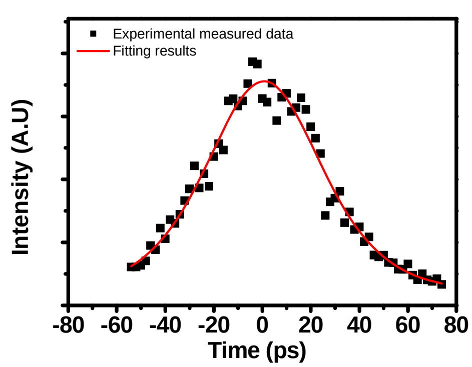

Fig. 4. The measured autocorrelation trace (solid squares) and fitting curve by $Sech^2$ function.

In Fig. 5, the pulse energies E_J of the Q-switching envelope were estimated by dividing the average output power P_0 into the repetition rate R_{ep} of the envelope. E_J shows increase tendency as the pump power increases. Due to apparently decrease of R_{ep} for the lower T_0 (Fig. 2(b)), E_J for T_0 =40% are higher than those of T_0 =55% and 80% in Fig. 5. At 15 W pumped power, the highest pulse energies of about 77 μJ can be obtained for R = 60% and T_0 = 40%. With the same T_0, the obtained pulse energies have no much difference for R = 80% and 60% due to similar average output power and repetition rate. However, the pulse

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energy and peak power for single ML pulse for R = 60% are higher than R = 80% due to less number of pulses in each Q-switched envelope or shorter Q-switched pulse width. The estimated pulse energy for each ML pulse is calculated by E_J/N that was presented in Table I. At 15W pump power, the highest peak power of ML pulses calculated by $P_p = \frac{P_0}{NR_{ep}t_0}$ is about 200 kW for R=60% and T_0=40%, where P_0 is the average output power, R_{ep} is the repetition rate of the Q-switched envelope, N is the number of pulses within a Q-switched envelope, and t_0 is the pulsewidth of the mode locking pulses.

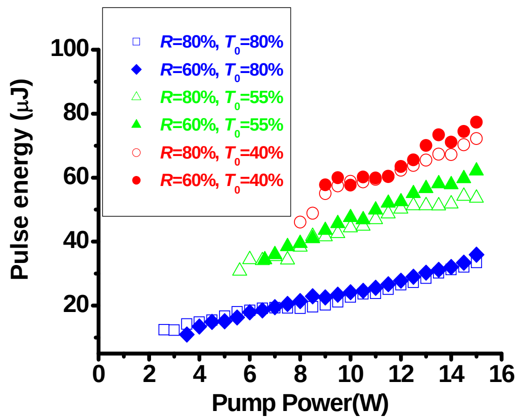

Fig. 5. The estimated pulse energy versus the pump power at the QML states with the T_0=80% (blue diamonds), 55% (green triangles), and 40% (red circles).

4. Conclusion

We have demonstrated the stable Q-switched and mode-locked operation of the Nd:$LuVO_4$ laser in use of the Cr^{4+}:YAG as the saturable absorber. The operation range of QML in use of the Cr^{4+}:YAG is larger than that use of SESAM and NLM. The obtained shape of Q-switched envelope, repetition rate and pulse energy are demonstrated to depend on the initial transmittance of the Cr^{4+}:YAG and reflectivity of the output coupler. Using R = 60% and T_0 = 40%, the highest pulse energy of 77 μJ of each Q-switched envelope, and the highest peak power about 200 kW of Q-switched mode-locked pulses can be obtained at 15 W pump power. It demonstrate the superior characteristic of the Nd:$LuVO_4$ crystal.

Acknowledgments

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