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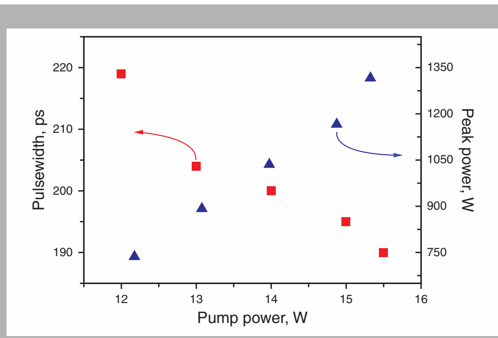
Abstract: Regular and robust Q-switched and mode-locked (QML) pulses are produced in $Nd:GdVO_4$ laser by the integration of nonlinear mirror and semiconductor saturable absorber mirror. The threshold of QML operation is increased by putting the SESAM in laser cavity with large beam radius. The nonlinear mirror absorber can further increase nonlinear loss modulation of pulses to produce the stable and periodic QML pulses.



Peak power and pulsewidth versus pump powers

Q-switched and mode-locked pulses generation in $Nd:GdVO_4$ laser with dual loss-modulation mechanism

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1. Introduction

Diode-pumped solid-state lasers (DPSL) have been of great interest due to the characteristics of longer lifetime, high stability, compactness, and portable for various applications. Various laser crystals, such as Ytterbium-doped [1,2] or Neodymium-doped laser crystals [3–6], are often used in DPSL for ultrashort and high peak power pulses generations. Neodymium-doped medium, especially vanadate crystals like Neodymium-doped Yttrium Orthovanadate crystal ($Nd:YVO_4$) and Neodymium-doped Gadolinium Orthovanadate ($Nd:GdVO_4$), are particularly suitable because of their high absorption and emission cross sections [5]. Although $Nd:GdVO_4$ has a reduced stimulated emission cross section in comparison with $Nd:YVO_4$, it has attracted much interest due to various superior natures including broader absorption bandwidth at 808 nm, higher thermal conductivity, and damage threshold. For operation at CW state with TEM_{00} mode output, $Nd:GdVO_4$ has been demonstrated to generate very large average output power (>100 W) [6] and show relative high conversion and slope efficiency [7].

Q-switching and continuous wave mode-locking (CW-ML) are widely used techniques in generating short pulses, which has also been reported in $Nd:GdVO_4$ lasers. In use of semiconductor saturable absorber mirrors (SESAM) [8, 9], CW-ML was demonstrated in $Nd:GdVO_4$ laser to generate multi-GHz repetition rate pulses having picosecond pulsewidth. Stankov proposed the nonlinear mirror mode-

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locking (NLM-ML) technique by using a second harmonic (SH) crystal and a dielectric mirror with high reflection coating for the SH wave and partial reflection coating for the fundamental wave [10]. NLM-ML can provide strong nonlinear loss modulation and generates CW-ML at low pump threshold in $Nd:GdVO_4$ laser [11]. Generally, the repetition rate of the CW-ML pulses are relatively high, which is restricted by the cavity length. Although high repetition pulses have various advantages such as in optical communication, optical switching and optical clocking, it will reduce pulse intensity and accumulate heat, leading to thermal lensing in optical nonlinearity measurements.

High energy pulses with lower pulse repetition rate can be generated by the Q-switching technique, such as that using the acousto-optical (AO) Q-switch modulator, SESAM, or $Co^{2+}:LaMgAl_{11}O_{19}$ absorber in a-cut and c-cut $Nd:GdVO_4$ lasers [12–14]. With the $LiF:F_2^-$ absorber, self-Raman conversion has also been reported in Q-switched $Nd:GdVO_4$ laser [15]. However, the generated Q-switched pulsewidth is comparative longer relative to the CW-ML pulses. Fortunately, Q-switched and mode-locked (QML) pulses, in which CW-ML pulses are modulated by long periodic Q-switched envelope, retains the characteristics of short pulse but reduces the pulse repetition rate. In $Nd:GdVO_4$ laser, QML pulses have been successful obtained using the Cr^{4+}:YAG [16, 17], low temperature GaAs absorber [18], and carbon nanotube [19] saturable absorber. By using SESAM as saturable absorber, QML can usually be observed before the completely CW-ML state is achieved as pump power increases [20].

Short pulses generation by dual loss-modulation devices has been widely reported recently due to variously practical advantages. A Q-switched laser by placing electro-optical modulator and GaAs saturate absorber inside the cavity is used to generate nanosecond pulse with symmetric shape [21]. Besides, the dual ML technique combining quadratic polarization switching and SESAM in multiple pass cavity, has been demonstrated in both $Nd:GdVO_4$ and $Nd:YVO_4$ lasers to generate low repetition rate pulses [22]. The results show that the dual ML design can improve the stability range of ML and reduce the risk of SESAM damage at high pump power. In addition, Schieffer et al. make use of the saturable Bragg mirror and cascaded $\chi^{(2)}:\chi^{(2)}$ nonlinearity to generate extremely stable sub-10 ps sech^2 pulses in $Nd:GdVO_4$ laser [23]. The stability and efficiency of NLM-ML $Nd:YVO_4$ laser can also be enhanced by the insertion of acousto-optical modulator inside the cavity to generate the QML pulses [24].

In this paper, we combine SESAM and NLM-ML techniques to generate low repetition rate and high peak power QML pulses in $Nd:GdVO_4$ laser. The SESAM is located at the position of large cavity beam radius to prevent it from damaging at high pump power. Due to the enhancement of nonlinear loss modulation of pulses, the operation range for robust and regular QML pulses generation would become wider as pump power changes. The shape of Q-switched envelope would also be more symmetric.

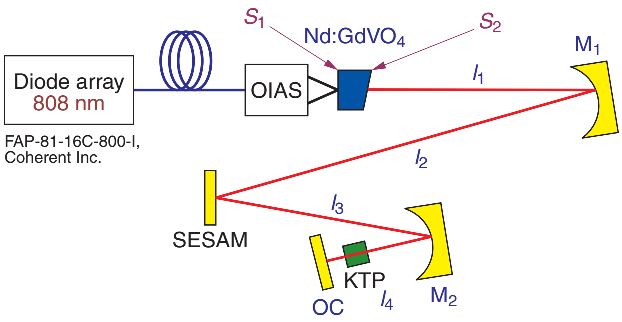

Figure 1 (online color at www.lphys.org) Experimental setup of $Nd:GdVO_4$ laser with dual ML technique

2. Experimental setup

The schematic laser setup is shown in Fig. 1. A fiber coupled diode array (FAP-81-16C-800-I, Coherent Inc.) with center wavelength of 808 nm is used as the pump source. The pump beam coming out from the fiber is imaged on the crystal through the 1:1.8 optical imaging accessories (OIA's, Coherent Inc.). An 8 mm-long $Nd:GdVO_4$ crystal (a-cut, 0.5-at.% Nd^{3+} concentration) is high-reflection (HR) coated at 1064 nm and anti-reflection (AR) coated at 808 nm on one side (S_1). The other side (S_2) is AR coated at 1064 nm and has 2° wedge. The resonator consists of two curved mirrors M_1 and M_2, with radius of curvatures of 500 mm and 200 mm, respectively; both mirrors are HR coated at 1064 nm and 532 nm. In addition, a SESAM (Batop Inc. modulation depth 1.6%, absorbance 3%, damage threshold 600 MW/cm^2) is placed between M_1 and M_2. By using ABCD Law, the radius of cavity mode on SESAM is estimated to be about 400 μm, which can prevent the SESAM from damaging at high pump power. The dichroic output coupler (OC), which has 80% reflectivity at 1064 nm and HR coated at 532 nm, is placed at the other end of laser cavity. The OC in combination with a 10-mm long type-II KTP crystal acts as nonlinear mirror (NLM) absorber that provide loss modulation of pulses.

The distances l_1 (from laser crystal to the M_1), l_2 (M_1 to SESAM), l_3 (SESAM to M_2), and l_4 (M_2 to OC) are 30 cm, 60 cm, 20 cm, and 11 cm, respectively. The laser crystal and KTP were wrapped with indium foils and mounted in water-cooled copper blocks where the water temperature was maintained at 15°C. The output power of the $Nd:GdVO_4$ laser were measured by a power meter and detector (Ophir Inc.) for both CW and ML states. The leakage radiation reflected from the wedged facet of the laser crystal was detected by a high speed InGaAs detector (Electro-Optics Technology Inc. ET 3000) that was connected to the oscilloscope (LeCroy LT372, bandwidth 500 MHz). A noncollinear autocorrelator with a 2-mm thick type-I BBO was placed outside the OC to measure the pulsewidth.

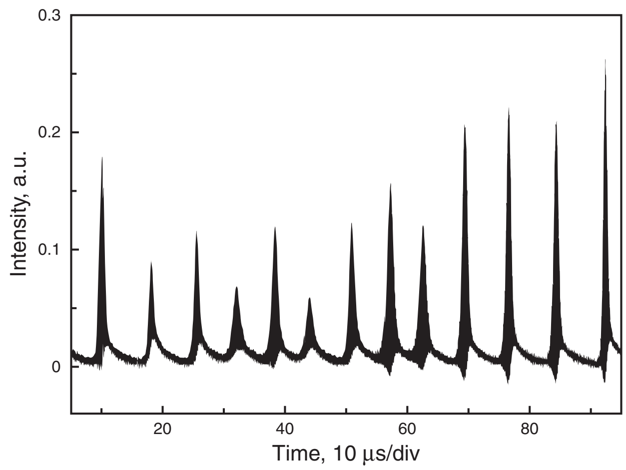

Figure 2 Time traces of Q-switched ML pulses at irregular state

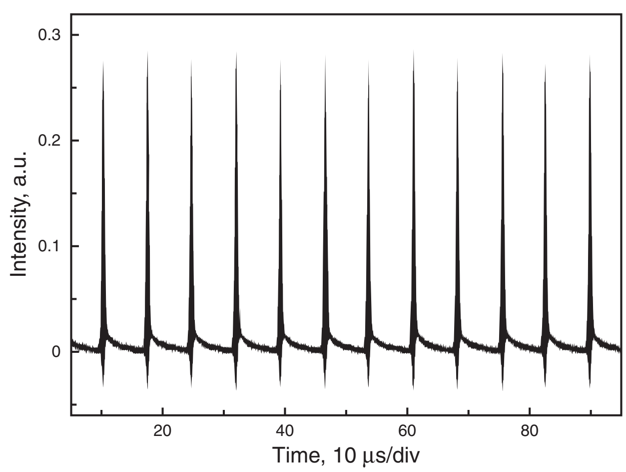

Figure 3 Time traces of Q-switched ML pulses at regular state

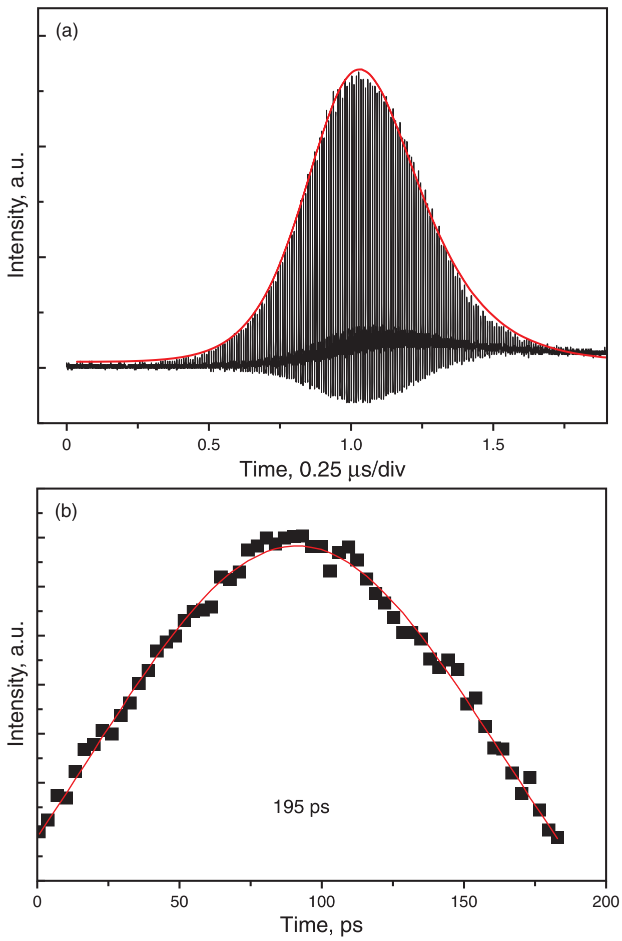

Figure 4 (online color at www.lphys.org) (a) Temporal expanding of QML pulse trains. (b) The measured autocorrelation trace

3. Results and discussions

By using only the SESAM and without the insertion of KTP in cavity, irregular QML pulse trains will be produced such as that shown in Fig. 2 for 12 W pump power. The Q-switched envelopes exhibit aperiodic, deformed shape and seriously time-varied amplitude fluctuation. Nevertheless, the QML pulse trains will become regular after the KTP is placed in front of the OC and the distance between them is properly adjusted, as shown in Fig. 1. The loss modulation depth of pulses will be enhanced by the action of nonlinear mirror absorber. The initial phase difference between fundamental wave and second harmonic wave will be π after light enters the KTP, reflected by OC and re-enters the KTP. Fig. 3 shows the regular QML trains, in which the amplitude variation was dramatically reduced and the width of envelope become shorter in comparison with Fig. 2. The period of Q-switched envelope also becomes fixed at about 140 kHz that corresponds to 7 μs spacing.

Fig. 4a shows the time expansion of the single QML pulse trains so that the ML pulses can be obviously seen. For the QML pulses generation with only one saturable absorber, the ML pulses are usually initiated above the ground level that can be seen in Fig. 2. Due to the enhancement of modulation depth from NLM saturable absorber, the ML pulses in the center of Q-switched envelope is started from the ground level. The time spacing between ML pulses is 7.7 ns that corresponds the cavity length of 121 cm. By fitting the QML envelope with the formula

$$I = \left[\frac{I_0}{\exp\left(\frac{1.76t}{\tau_1}\right) + \exp\left(-\frac{1.76t}{\tau_2}\right)} \right]^2 , \qquad (1)$$

we can estimate the rise-time $t_1 = 0.59$ μs and fall-time $t_2 = 0.37$ μs for the temporal profile of QML envelope. The pulsewidth of QML pulses, measured by a home-made autocorrelator, is about 195 ps as shown in Fig. 4b.

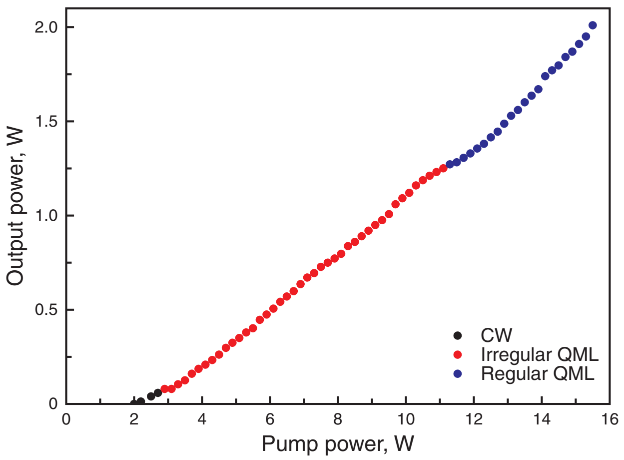

Figure 5 (online color at www.lphys.org) Output powers of $Nd:GdVO_4$ laser at CW (black circles), irregular QML (red circles), and regular QML (blue circles) states versus pump powers

The output power versus the pump power with KTP insertion is shown in Fig. 5. The threshold pump power P_p for CW lasing (black circles) is 2 W and the slope efficiency is 10%. The laser will turn into irregular QML state (red circles, like Fig. 2) at $P_p = 2.9$ W and generate stable and regular QML pulses (blue circles, like Fig. 3) at $P_p = 11.3$ W. By using only nonlinear mirror mode-locking technology in $Nd:GdVO_4$ laser, the laser transfers to CW-ML state at relative low pump power of $P_p = 2.3$ W [11]. Besides, in [11], the laser has relative short stable QML operation range between CW and ML state as pump power increase. For generating high peak power QML pulses here, the threshold pump power for stable QML generation is raised. Besides, the stable operation range of QML state is increased as P_p is varied from 11.3 W to 15.5 W. The highest output power of 2.1 W can be generate at the pump power of 15.5 W.

The measured pulsewidth and the estimated peak power for regular QML pulses are shown in Fig. 6. The pulsewidth shows slight decrease from 219 ps to 190 ps as pump power increases from 12 W to 15.5 W. However, the repetition rate of QML envelope does not show obvious variation and fix at about 140 kHz. The peak power of QML pulses shows linear increase from 0.74 kW to 1.3 kW. In this estimation, we considers Q-switched modulation frequency of 140 kHz, and assuming 60 pulses in each Q-switching envelope. Although multiple pass cavity can greatly reduce the cavity repetition rate and increase the peak power of CW-ML pulses, it needs relative high threshold for CW lasing (P_p above 10 W) and CW-ML (P_p near 20 W) as well as relative complicated cavity setup [22]. Our configurations propose a simple cavity setup for generating QML pulses to reduce the pulse repetition rate and enhance the peak power by using the dual ML technique.

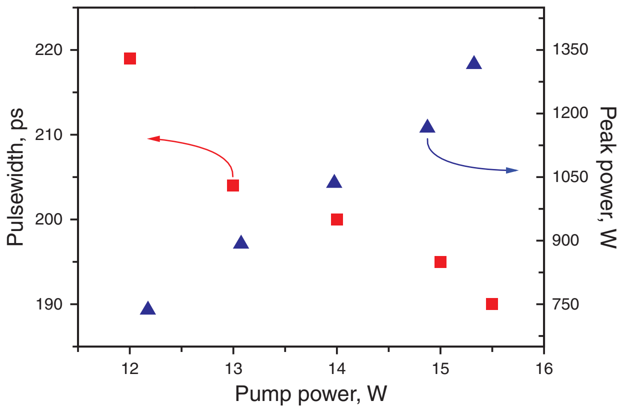

Figure 6 (online color at www.lphys.org) Peak power and pulsewidth of QML pulses versus pump powers

4. Conclusions

Regular and robust QML operation has been demonstrated in $Nd:GdVO_4$ laser using the dual loss-modulation mechanism. A semiconductor saturable absorber mirror is put at the position with large cavity beam radius to prevent it from damaging at high intra-cavity peak power. In addition, the nonlinear mirror mode-locking technique was used simultaneously to enhance the nonlinear loss modulation depth of pulses and stabilize QML pulses. As a result, robust QML pulses can be generated at higher pump power and the operation range of stable QML state is also increased. For 15.5 W pump power, the highest average output power of QML pulses is about 2.1 W, corresponding to peak power of 1.3 kW.

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