Comparative studies of semiconductor saturable absorber mirror mode-locking dynamics in pulsed diode-end-pumped picosecond Nd:GdVO$_4$ and Nd:YAG lasers

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Received November 10, 2005

Ultrashort pulses were generated in passively mode-locked Nd:YAG and Nd:GdVO$_4$ lasers pumped by a pulsed laser diode with 10-Hz repetition rate. Stable mode-locked pulse trains were produced with the pulse width of 10 ps. The evolution of the mode-locked pulse was observed in the experiment and was discussed in detail. Comparing the pulse evolutions of Nd:YAG and Nd:GdVO$_4$ lasers, we found that the buildup time of the steady-state mode-locking with semiconductor saturable absorber mirrors (SESAMs) was relevant to the upper-state lifetime and the emission cross-section of the gain medium.

OCIS codes: 140.4050, 140.3480, 140.3530, 140.3070.

In recent years all solid-state passively mode-locked lasers operating in the infrared spectral regions have wide applications in the fields of industry, defense, medical treatment, and scientific research. Nd:YAG and Nd:GdVO$_4$ are favorable laser materials for the generation of ultrashort pulses with various mode-locking techniques such as active modulation, additive-pulse mode locking[1,2], self-mode locking, and mode locking by various semiconductor saturable absorber mirrors (SESAMs)[3−9]. Among the various mode-locking techniques, mode-locking by semiconductor absorber mirrors is very favorable for picosecond system. Generally the lasers are pumped by continuous wave (CW) laser diodes (LDs), the output powers of which limit the peak powers and pulse energies of the ultrashort pulses. One can achieve higher peak powers by pumping the laser with pulsed diode-laser. Heinaz *et al.* reported the pulsed diode-pumped additive-pulse mode-locked laser[1]. Sun *et al.*[10] reported the pulsed diode-side-pumped mode locking with SESAM, but the evolution of the stable mode locked pulse was not discussed in detail.

In this letter we discuss pulsed diode-end-pumped mode-locked Nd:YAG and Nd:GdVO$_4$ lasers with SESAM, which generates stable mode-locked pulse trains and shows the evolution of mode locked pulse in the laser. The single-pulse energy of two laser is about 15 nJ, which is three times higher than that of CW system under the same conditions. The pulse duration is found to be $\leq$ 10 ps. The evolutions of the stable mode-locked pulse for two lasers are discussed in detail. We find that the buildup time of the steady-state mode-locking with SESAMs is relevant to the upper-state lifetime and the emission cross-section of the gain medium.

The experimental setup, as shown in Fig. 1 has no astigmatism and is easy to ensure pure fundamental mode operation. The pump radiation was provided by a pulsed fiber-coupled LD operating at a wavelength near 808 nm. The pump beam from the fiber end was focused onto the laser crystal with a spot diameter of about 160 μm. The Nd:YAG ($\phi 3 \times 5$ (mm)) and Nd:GdVO$_4$ ($3 \times 3 \times 5$ (mm)) laser crystals used in our experiments had Nd^{3+} concentration of 1 at.-%. L$_3$ was a convex lens with the focal length of 100 mm, which was used to compensate the thermal lensing effect in the crystal. Changing the focal length of the focusing lens L$_4$ and the distance between L$_4$ and SESAM adjusts the laser spot on the SESAM. Adjusting the angle of output coupler M in the cavity changes the output coefficient. At the angle of about 10° the best output of 7% transmission for per output beam at the oscillating wavelength was obtained. A SESAM consisting of a single 12-nm In$_{0.25}$Ga$_{0.75}$As quantum well on AlGaAs Bragg mirror structure was employed to achieve mode locking. The time response of the absorber was characterized via reflection pump-probe measurements at 1064 nm. The heat loaded on the SESAM was handled simply by mounting it on a small copper heat sink.

In the experiment, the laser operating at a 10-Hz repetition rate with a pulsed diode-pumped system, we obtained stable mode-locking with the crystals Nd:YAG and Nd:GdVO$_4$ as shown in Figs. 2 and 4 respectively. The pulse width of the two lasers was about the same order as that in Ref. [6]. The pulse duration was about $\leq$ 10 ps. In the experiment the pulse energies were measured indirectly, we found that the pulse energy of Nd:GdVO$_4$ laser was a little higher than that of Nd:YAG. The single-

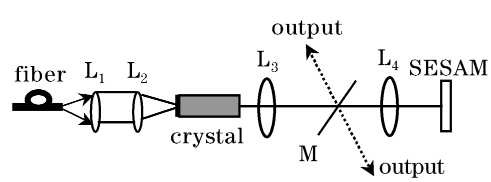

Fig. 1. Schematic of the laser setup.

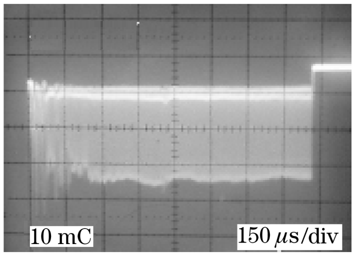

Fig. 2. Oscilloscope trace of the pulse train illustrating the stable mode-locking of the Nd:YAG laser.

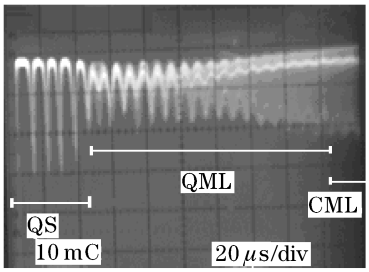

Fig. 3. Oscilloscope trace of the beginning part of the pulse train illustrating the three stages of pulse evolution of Nd:YAG laser.

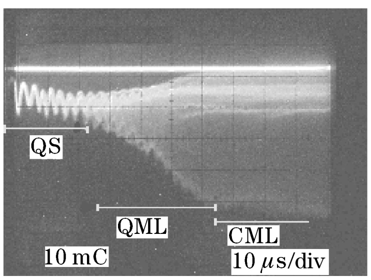

Fig. 4. Oscilloscope trace of the beginning part of the pulse train illustrating the three stages of pulse evolution of Nd:$GdVO_4$ laser.

pulse energy of Nd:$GdVO_4$ laser was about 15 nJ, which is three times higher than that of CW system under the same conditions.

In the experiment the evolutions of the pulses in the laser were observed as illustrated in Figs. 3 and 4. We divided the evolution into three stages. 1) In the beginning of laser emission, the average intracavity power was low, and the SESAM just played the role of a loss element in the cavity and the laser emission started from the relaxation oscillation, so self-Q-switching (QS) occured. One can see that QS of the crystal Nd:YAG is strong, while QS of the crystal Nd:$GdVO_4$ is not distinct contrasting to the crystal Nd:YAG. This is because that the upper-state lifetime of Nd:YAG (230 μs) is longer than that of Nd:$GdVO_4$ (90 μs). The tendency of laser to Q-switching increases with the upper-state lifetime. This phenomenon is in good agreement with the theoretic analysis[11]. 2) As the circulating energy inside the cavity increased and the SESAM began to modulate the laser, self-Q-switched mode-locking (QML) generated. In this stage one can see that the durations of QML of Nd:$GdVO_4$ and Nd:YAG are about 40 and 160 μs, respectively. The duration of QML of Nd:$GdVO_4$ is

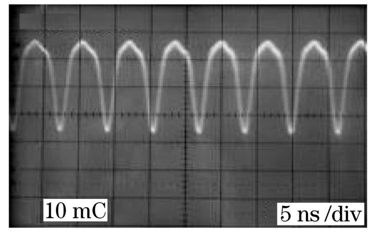

Fig. 5. Individual pulses of the stable mode-locked pulse train.

shorter than that of Nd:YAG. This is because that the crystal Nd:$GdVO_4$ with shorter upper-state lifetime and larger emission cross-section can efficiently decrease the QML more than Nd:YAG[6−8]. 3) After many cavity round trips, stable CW mode-locking (CML) set in and a picosecond pulse train with relative constant amplitude followed. With the time base of 5 ns/division one can resolve individual pulses (see Fig. 5), and the pulse repetition rate is 154 MHz.

For the second and the third stages we can make an explain as follows. The minimum intracavity pulse energy E_{pc}, which is required for obtaining stable CML, is described as[9]

$$E_{pc} \equiv (F_{sat,L} A_{eff,L} F_{sat,A} A_{eff,A} \Delta R)^{1/2}, \quad (1)$$

where $F_{sat,L} = h\nu/(m\sigma_L)$ is the saturation fluence of the gain, $A_{eff,L}$ the effective laser mode area in the gain, $F_{sat,A}$ the saturation fluence of absorber, $A_{eff,A}$ the effective laser mode area on the saturable absorber. The energy of a mode-locked pulse in the cavity is defined as E_p. As $E_p > E_{p,c}$ laser operates in CML, as $E_p < E_{p,c}$ laser operates in QML. In our experiment $A_{eff,L}$, $A_{eff,A}$, $F_{sat,A}$, and ΔR are constant, but $F_{sat,L}$ is variable with the emission cross section σ_L of the gain medium. The emission cross section of Nd:$GdVO_4$ (7.6×10^{-19} cm^2) is larger than that of Nd:YAG (2.8×10^{-19} cm^2), so the minimum intracavity pulse energy E_{pc} of Nd:$GdVO_4$ laser is lower than that of Nd:YAG laser, that is to say Nd:$GdVO_4$laser is easier to CML than Nd:YAG laser. So the buildup time of steady mode-locking of Nd:$GdVO_4$laser is shorter than that of Nd:YAG laser. Our experimental results agree well with the theoretical study and provide good proof to understand the mechanism of mode-locking with SESAM.

Figures 3 and 4 show that the buildup times of the steady-state mode-locking are about 200 and 70 μs for Nd:YAG and Nd:$GdVO_4$ respectively, which are close to the upper-state lifetimes of the two crystals (230 and 90 μs). That is to say the buildup of steady-state mode-locking by SESAM is relevant to the upper-state lifetime of the crystal. In the experiment, we also found when the pulse width of pump light is longer than the buildup time of the stable mode-locking, the width of the stable mode-locked pulse train decreased with the decrease of the pulse width of pump light (see Figs. 6 and 7). The result is so important that one can pick out the stable mode-locked pulse from the mode locked pulse train with a proper pump width and a proper delay time, which will be discussed in another paper.

In this letter we discussed the pulsed diode-pumped

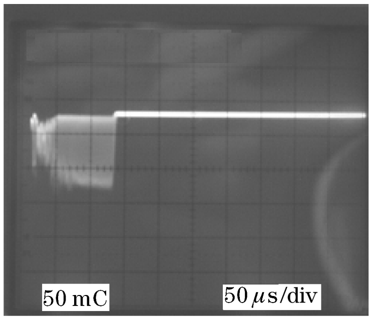

Fig. 6. Mode-locked pulse train with the pump pusle duration of 120 μs.

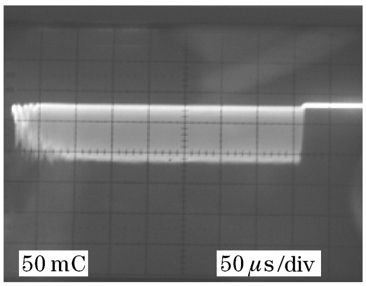

Fig. 7. Mode-locked pulse train with the pump pulse duration of 400 μs.

mode-locked Nd:YAG and Nd:GdVO$_4$ lasers with a SESAM at 10-Hz repetition rate, obtained stable mode-locking, observed three stages of the pulse evolution. Comparing the pulse evolutions of two lasers we found that the buildup time of the steady-state mode-locking is relevant to the upper-state lifetime of the gain medium. The single-pulse energy of two lasers is about 15 nJ, which is three times higher than that of CW system under the same conditions. The pulse duration is found to be $\leq$ 10 ps. Employing the system the life of the diode laser can be improved, and higher single-pulse energy can be obtained with higher pump energy.

This work was supported by the National Nature Science Foundation of Beijing under Grant No. 3021001 and the foundation of Liaocheng University. B. Zhang's e-mail address is zhangbingyuan@sina.com.cn.

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