# Passive Mode Locking in a Diode-Pumped $Nd:GdVO_4$ Laser With a Semiconductor Saturable Absorber Mirror

Sanjun Zhang, E Wu, Haifeng Pan, and Heping Zeng

*Abstract*—**We demonstrate $Q$-switched and CW passive mode locking in a laser-diode-pumped $Nd:GdVO_4$ laser with a semiconductor saturable absorber mirror. The repetition rate of the $Q$-switched envelope increased from 23.1 to 260 kHz as the pump power increased from 1.75 to 13.0 W. At a pump power of 13.7 W, the $Q$-switched mode locking changed to CW mode locking. The maximum average output power of 4.9 W with a 140-MHz repetition rate was obtained at a pump power of 17.9 W and the single mode-locked pulse energy was 0.035 $\mu$J. The CW mode-locked pulse duration was measured to be $\sim$11.5 ps.**

*Index Terms*—**CW mode locking, diode-pumped solid-state laser, $Nd:GdVO_4$, $Q$-switched mode-locking.**

THE neodymium ion doped laser material $Nd:GdVO_4$ has recently become the focus of interest for its good physical, optical, and mechanical properties. Compared with its isomorph $Nd:YVO_4$, $Nd:GdVO_4$ exhibits a larger absorption cross section [1]. Its broad absorption band matches well the emission band of GaAlAs laser diodes, making it quite suitable to take the full advantages of diode pumping for compact all-solid lasers. Also, its relatively broad gain bandwidth makes it favorable for mode-locking operation. It is well known that a broad emission bandwidth is necessary for generating narrow laser pulses. The emission bandwidth of $Nd:GdVO_4$ (1.25 nm) is much broader than that of $Nd:YVO_4$ (0.8 nm), which will result in a much narrower mode-locked pulse duration in a $Nd:GdVO_4$ laser than in a $Nd:YVO_4$ laser. We have reported $Q$-switched mode locking in a diode-pumped $Nd:GdVO_4$ laser with an intracavity $Cr^{4+}$ : YAG [3], which confirmed the excellent mode-locking laser performance of $Nd:GdVO_4$. Most importantly, $Nd:GdVO_4$ crystals have unexpectedly high thermal conductivity along the $\langle 110 \rangle$ direction [2], comparable to that of YAG and much higher than that of $Nd:YVO_4$, which provides the desirable advantage for high-power lasers. All of the above properties make $Nd:GdVO_4$ a good candidate for high-peak-power mode-locked lasers for various applications such as material processing, communications, signal processing, biomedicine, and nonlinear frequency conversion. In this paper, we report CW mode locking as well as $Q$-switched mode locking in a diode-pumped $Nd:GdVO_4$ laser with a semiconductor saturable absorber mirror (SESAM), which is, to the best of our knowledge, the first time anyone has obtained $Q$-switched mode-locked (QML) and CW mode-locked (CML) pulse trains from a $Nd:GdVO_4$ laser.

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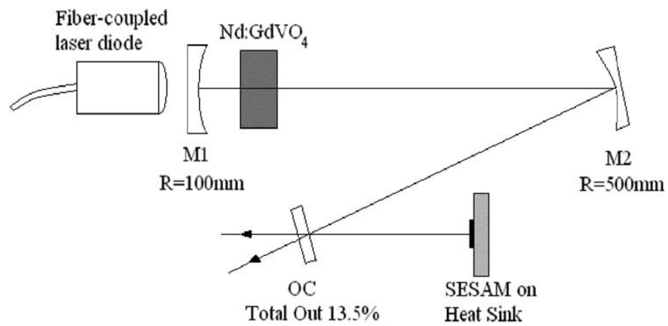


Fig. 1. Cavity configuration of the passively mode-locked $Nd:GdVO_4$ laser.

SESAM, as an intracavity saturable absorber first introduced by Keller *et al.* in 1992 [4], has been successfully used to mode lock a wide range of lasers, such as neodymium ion-doped lasers with Nd:YLF [4], Nd:YAG [5], $Nd:YVO_4$ [6] Nd:LSB [7], and Nd:glass [8]. In contrast to ion-doped crystal saturable absorbers, SESAMs can be adapted to many wavelengths by using different combinations of semiconductor layers and material parameters. The variable key parameters of SESAM, such as recovery time and saturation fluence, offer advantages over other saturable absorbers in passively mode-locked lasers. In addition, the SESAM can be used as a cavity mirror, which makes the insertion loss much lower while the laser is much more compact. In our experiment, the $Nd:GdVO_4$ laser was mode locked by a piece of SESAM from BATOP optoelectronics. The saturable absorber mirror (SAM) was a Bragg mirror of AlAs–GaAs, on top of which there was an InGaAs single quantum well (QW) and a single oxide protection layer. It was fabricated by using solid-source molecular beam epitaxy (MBE). The absorbing QW was grown at a low temperature to include extra arsenic clusters for fast relaxation of the excited carriers.

Our schematic experimental setup is shown in Fig. 1. The pump power was from a 20-W fiber-coupled laser-diode array with the emission wavelength at 808 nm controlled by a thermal regulation. The fiber core had a diameter of 400 $\mu$m and a numerical aperture of 0.22. The pump laser beam was focused by a series of lenses on the 3-mm-long, a-cut, and 1-at.% $Nd^{3+}$-doped $Nd:GdVO_4$ crystal. It was wrapped around with indium foil and fixed in a water-cooled copper heat sink at

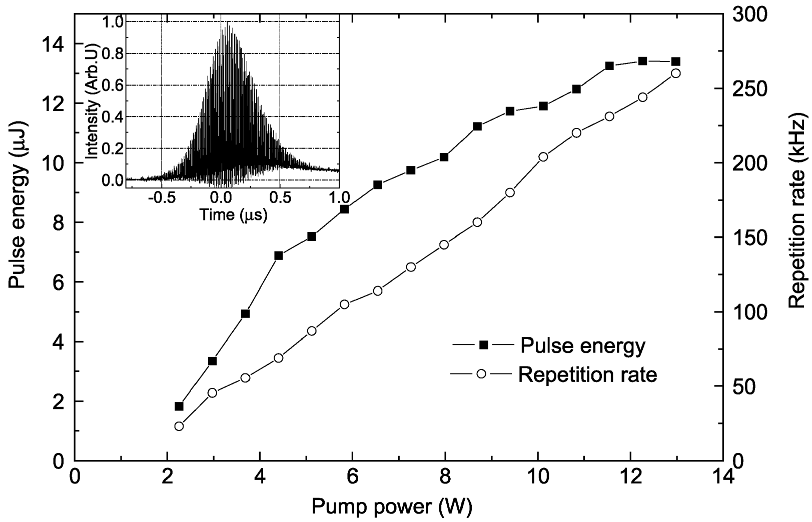


Fig. 2. Dependence of the pulse energy and repetition rate of the $Nd:GdVO_4$ laser at QML state on the incident pump power. Inset: the QML pulse envelope.

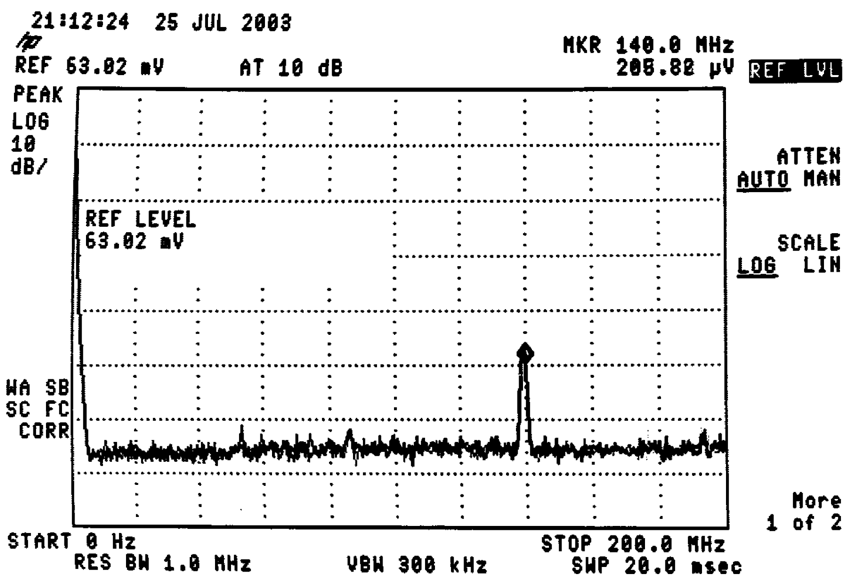


Fig. 3. Power spectrum analyzer signal for the CW mode-locked $Nd:GdVO_4$ laser.

15.5 °C. Since the laser propagated along the $\langle 100 \rangle$ direction of the $Nd:GdVO_4$ crystal and the thermal conductivity of the crystal along the $\langle 110 \rangle$ direction was very large, the heat could be dispelled by the heat sink easily. The laser cavity consisted of a SESAM and three other mirrors: an input concave mirror M1 ($R = 100$ mm) with high transmission at 808 nm and high reflection at 1064 nm, a folded concave mirror M2($R = 500$ mm) with high reflection at 1064 nm, and an output coupler (OC) flat mirror. The OC mirror had a reflectivity of 93% at 1064 nm, giving a total output coupling of ~13.5%. The length between M1 and M2 was about 60 cm, between M2 and OC about 30 cm, and between OC and SESAM about 17 cm. In this arrangement, the total cavity length added up to 107 cm. The center wavelength of the SESAM in our experiment was 1064 ± 5 nm. In addition, the saturation fluence was measured to be $\sim 70$ $\mu$J/cm$^2$ using the pump-probe method by the manufacturer (BATOP Optoelectronics, Germany). The saturation absorption was 2.0%, while the nonsaturable loss was less than 0.3%, and the relaxation time was 20 ps. The SESAM was mounted on a thermoelectric device and the temperature was set to 20 °C. We designed the laser cavity with great care to allow mode matching with the pump beam and to provide the proper spot size on the SESAM.

The mode-locked laser began to operate when the pump power exceeded 1.75 W. The low threshold indicates the low insertion loss of the SESAM. Slightly increasing the pump power, a QML state was initiated. The repetition rate of the $Q$-switched pulse envelope increased linearly from 23.1 to 260 kHz as the pump power increased from 1.75 to 13 W, as shown in Fig. 2. The inset is the oscilloscope trace of the $Q$-switched pulse envelope with the pulse duration of ~500 ns. Increasing the pump power further, the QML state transformed into a CML state. In our experiment, the self-started CML operation was achieved when the pump power increased up to about 13.7 W. We monitored the power spectrum on a spectrum analyzer (Hewlett Packard 8591E). Fig. 3 displays the power spectrum for the CML $Nd:GdVO_4$ laser. One can see clearly that the CML laser operated at 140 MHz and no

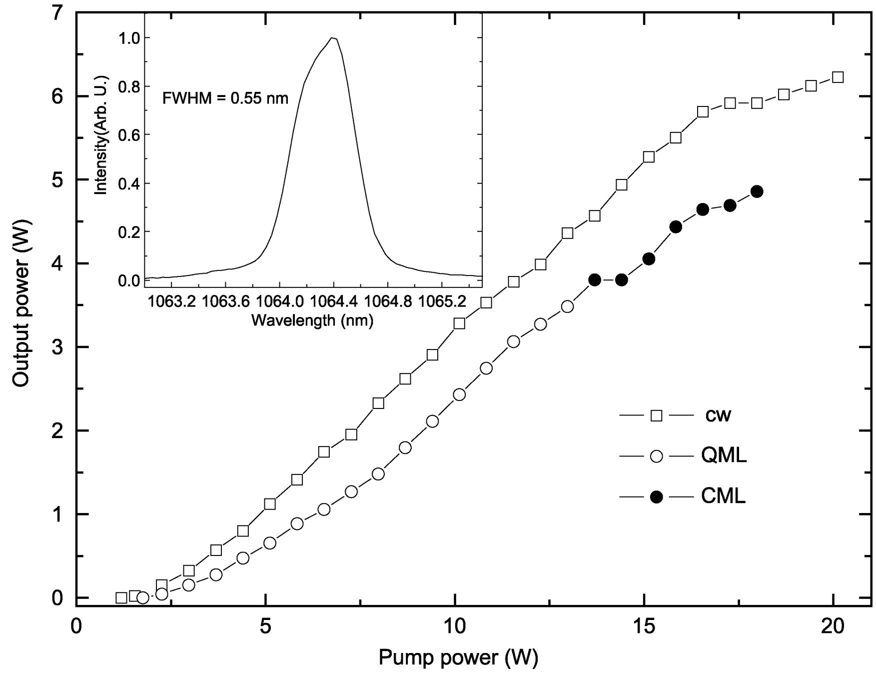


Fig. 4. Dependence of the CW output power and the average output power of the passively CML Nd:GdVO$_4$ laser on the incident pump power. Inset: the optical spectrum.

QML side-bands existed. Fig. 4 indicates the dependence of the CW output power and the average output power of the QML and CML pulses on the incident pump power. When the pump power was less than 13.0 W, the Nd:GdVO$_4$ laser operated in QML states. The maximum average output power of 3.5 W with the maximum single $Q$-switched pulse energy of 13.4 $\mu$J was obtained at the pump power of 13.0 W. The CML pulses were obtained when the pump power exceeded 13.6 W. We obtained an average power of 4.9 W from the CML Nd:GdVO$_4$ laser at a pump power of 17.9 W. The damage of the SESAM was observed in our experiment, and for this reason we did not increase the pump power further. The slope efficiency for the mode-locked Nd:GdVO$_4$ laser was 33.4%. We replaced the SESAM by a high reflection mirror and the CW output power was measured under the same conditions. As shown in Fig. 4, when the Nd:GdVO$_4$ laser was operated in the CW state, the slope efficiency was 36.8%, and the maximum output power of 6.2 W was obtained when the pump power was 20.0 W. In order to generate a high output power, the heat in the crystal must be removed rapidly, otherwise the thermal lens effect will decrease the stability of the laser and therefore decrease the output power. Fortunately, Nd:GdVO$_4$ crystals possess a large thermal conductivity. In our experiment, even in the condition of high pump power, the heat could be removed simultaneously and the thermal lens effect was negligible. This confirmed the good thermal conductivity of Nd:GdVO$_4$ crystal.

For the mode-locking lasers with a SESAM, the transforming condition from a QML state to the CML state could be explained as follows. To obtain stable CW mode locking, the intracavity pulse energy $E_P$ should exceed a critical threshold value, which is related to the saturation parameter $S$ given by [9]

$$E_p > E_{L,\text{sat}} \frac{\Delta R}{S} \tag{1}$$

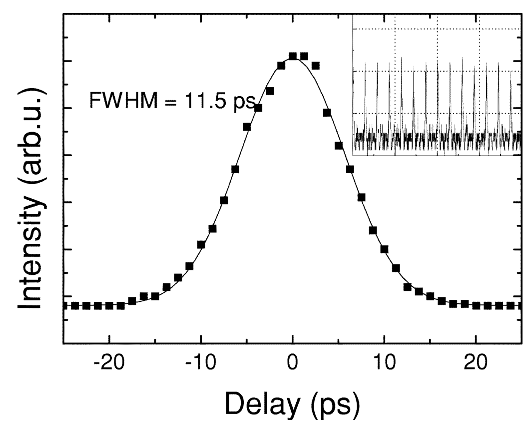


Fig. 5. Autocorrelation of the CW mode-locked Nd:GdVO$_4$ laser. The 140-MHz repetition rate of the CML pulses is shown in the inset.

where $E_{L,\text{sat}}$ is the saturation energy of the gain [9], [10] and $\Delta R$ is the modulation depth of the SESAM, which was 1.7% for our SESAM. Its physical background is explained in that the pulse energy $E_P$ must be sufficiently strong to saturate the gain material, under these conditions, the laser was operated in the stable CML state [10]. Typically, the saturation parameter $S$ was taken as $S \approx 3 \sim 5$ for low-power lasers, whereas for suppressing the $Q$-switching instability a bigger $S$ was needed for high-power lasers [9]. The value of $S \approx 27$ was used in an Nd:YAG laser with an average output of 10.7 W [11]. In our experiment, the saturation parameter $S$ was calculated to be 17.5, and it is needed to suppress the $Q$-switching instability for our high-power laser. The CML pulse duration, as shown in Fig. 5, was measured to be 11.5 ps [full-width at half-maximum (FWHM)] by a homemade autocorrelator with a KNbO$_3$ crystal under type- II phase-matched second-harmonic interaction in a noncollinear configuration. The inset is the CML pulses with a repetition rate of 140 MHz. The maximum average output power of 4.9 W was obtained at a pump power of 17.9 W. The peak power was calculated to be 3.0 kW. The optical spectrum of the CML Nd:GdVO$_4$ laser was displayed in the inset of Fig. 4. The wavelength was centered at 1064.4 nm with a bandwidth (FWHM) of 0.55 nm. The time–bandwidth product was calculated to be 1.7. Obviously, it was not transform-limited and the optical spectrum (0.55 nm) did not reach the bandwidth ability of Nd:GdVO$_4$ (1.25 nm). Probably, it was the SESAM recovery time (20 ps) or the crystal dispersion that limited the mode-locked pulse. At the same time, an 8-mm-long, a-cut, 0.27-at.% Nd$^{3+}$-doped Nd:YVO$_4$ crystal was also tested in our experiment; the duration of Nd:YVO$_4$, which was measured to be about 21 ps, was longer than that of Nd:GdVO$_4$ ($\sim$11.5 ps), which indicates that Nd:GdVO$_4$ is superior to Nd:YVO$_4$ in the mode-locking region.

In conclusion, we demonstrated a $Q$-switched mode-locked and CW mode-locked Nd:GdVO$_4$ laser by using a SESAM. The maximum average output power of the QML operation was 3.5 W and the envelope of the $Q$-switched pulse was $\sim$500 ns. At a pump power of 13.6 W, the $Q$-switched mode-locking region changed to the CW mode-locking region. The 140-MHz mode-locked pulse train with a pulse duration $\sim$11.5 ps was obtained. The maximum average output power was 4.9 W, the maximum single-pulse energy reached 0.035 $\mu$J, and the peak power was 3.0 kW. The results in our study confirmed again the excellent laser performance of Nd:GdVO$_4$.

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