



Q-switched mode-locking by Cr^{4+} :YAG in a laser-diode-pumped c-cut $\text{Nd}:\text{GdVO}_4$ laser

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Abstract

We demonstrated passively Q-switched mode-locking in a laser-diode pumped c-cut $\text{Nd}:\text{GdVO}_4$ laser with a Cr^{4+} :YAG crystal as the intracavity saturable absorber. At a pump power of 17.3 W, the Q-switched envelope repetition rate was 37 kHz with the maximum average output power of 2.1 W, while the mode-locked pulses within the Q-switched envelope had a repetition rate of 143 MHz. Experimental comparison between c-cut and a-cut $\text{Nd}:\text{GdVO}_4$ lasers indicated that the c-cut $\text{Nd}:\text{GdVO}_4$ was more suitable for Q-switched mode-locking.

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Neodymium ion-hosted crystals have been widely used to construct compact laser-diode pumped solid-state lasers in the near-infrared region. Recently, $\text{Nd}:\text{GdVO}_4$, as a novel isomorph of $\text{Nd}:\text{YVO}_4$, has attracted great attention since its development due to its excellent physical, optical, and mechanical properties. Compared with $\text{Nd}:\text{YVO}_4$, $\text{Nd}:\text{GdVO}_4$ exhibits larger absorption cross section ($5.2 \times 10^{-19} \text{ cm}^2$) [1]. And its absorption band matches well the emission band of

GaAlAs laser diode, making it quite suitable to take the full advantages of diode pumping for compact all-solid-state lasers. Most importantly, $\text{Nd}:\text{GdVO}_4$ possesses a much higher thermal conductivity than $\text{Nd}:\text{YVO}_4$ [2], which is quite useful to obtain high-power lasers. Various $\text{Nd}:\text{GdVO}_4$ lasers operated at different emission wavelengths have been achieved [3–6]. And both actively and passively Q-switched $\text{Nd}:\text{GdVO}_4$ lasers have also been realized [7,8]. Recent experiments indicated that, under identical pumping conditions and laser configurations, $\text{Nd}:\text{GdVO}_4$ lasers had higher output power and higher slope efficiencies than $\text{Nd}:\text{YVO}_4$ lasers [3–9]. Up to now, Q-switched mode-locking has been achieved in some neodymium ion hosted crystals,

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such as Nd:YAG and Nd:YVO₄ [10–13]. The emission bandwidth of Nd:GdVO₄ (1.25 nm) is broader than that of Nd:YVO₄ (0.8 nm), which makes it favorable for generating narrower mode-locked laser pulses. We have reported passive mode-locking in a diode-pumped a-cut Nd:GdVO₄ laser with a SESAM [14]. The mode-locked pulse durations of Nd:GdVO₄ and Nd:YVO₄ were measured to be 11.5 and 21 ps, respectively, which indicated that Nd:GdVO₄ is more competent than Nd:YVO₄ when operated in mode-locked state. Passively Q-switched c-cut Nd:GdVO₄ laser has been reported in [8]. As compared with Q-switched a-cut Nd:GdVO₄ laser, the c-cut Nd:GdVO₄ laser had a lower repetition rate and a narrower laser pulse. All these features enabled the corresponding Q-switched pulses to have much higher peak power. Consequently, the c-cut Nd:GdVO₄ should be suitable for high-peak-power laser operation. In this paper, we report on a passively Q-switched mode-locked (QML) c-cut Nd:GdVO₄ laser with a Cr⁴⁺:YAG saturable absorber, and an experimental comparison between the passively QML c-cut and a-cut Nd:GdVO₄ lasers.

Cr⁴⁺:YAG crystal has a saturable absorption in the range of 0.9–1.2 μm. For this reason, the Cr⁴⁺:YAG crystal has been used widely to generate nanosecond Q-switched and picosecond mode-locked laser pulses in the near infrared region, especially in the Nd³⁺ ions-doped lasers that run at 1.06 μm. When the intracavity laser intensity is low, most of Cr⁴⁺ ions are populated in the ground state. Since the relaxation time for the first excited state is in the microsecond region [15,16], Cr⁴⁺:YAG crystal only functions as an effective intracavity saturable absorber for Q-switching. While the intracavity laser intensity is sufficiently high, the excited state absorption (ESA) in Cr⁴⁺:YAG, which excites Cr⁴⁺ ions from the first excited state to the higher-lying levels, plays an important role in the pulsed laser performance. Further excitation by strong ESA promotes an accumulation of the Cr⁴⁺ ions in the higher-lying levels, leading to saturation of the ESA. Since the relaxation time of the ESA is in the subnanosecond region [15,16], the intracavity laser intensity should be large enough to saturate the ESA in order to achieve a passive mode-locking [13]. For this pur-

pose, high pump power must be cast to the laser active materials, the large absorption and emission cross section of Nd:GdVO₄ enable efficient diode pumping to achieve high-power laser operation, and its large thermal conductivity is favorable for dispelling the enormous heat in the laser crystal, which makes it relatively easy to obtain sufficient intracavity laser intensity to saturate the ESA of Cr⁴⁺:YAG for mode-locking operation.

The schematic of our experimental setup is shown in Fig. 1. The pump power was supplied by a 20-W fiber-coupled laser-diode array with the emission wavelength at 808 nm controlled by a thermal regulation. The diameter and numerical aperture of the fiber core were 400 and 0.22 μm, respectively. The pump laser beam was focused by a series of lenses with a beam spot about 600 μm on the Nd:GdVO₄ crystal. The laser resonator consisted of three 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. OC mirrors with various transmissions at 1064 nm were tested in our experiment. The length between M1 and M2 was about 60 cm and the length between M2 and OC about 45 cm. In this arrangement, the total cavity length added up to 105 cm. Three millimeter-long, 1-at% Nd³⁺ doped c-cut and a-cut Nd:GdVO₄ crystals were used as the laser active materials, which were wrapped with indium foil and fixed in a water-cooled copper heat sink. The temperature of water was controlled at 15.5 °C. The Nd:GdVO₄ crystals were placed near M1 and the Cr⁴⁺:YAG crystal near the OC mirror.

In order to optimize the passively QML c-cut Nd:GdVO₄ laser, various OC mirrors with transmissions of 7%, 17%, 30% and Cr⁴⁺:YAG crystals

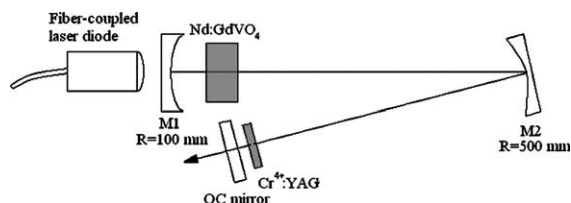


Fig. 1. Cavity configuration of the passively QML c-cut and a-cut Nd:GdVO₄ lasers.

with initial transmission of 90% and 85% were tested, respectively, in our experiment. We found that an OC mirror with transmission of 7% at 1064 nm together with a Cr⁴⁺:YAG crystal of an initial transmission $T_0 = 90\%$ gave the optimum laser performance. Fig. 2 shows the dependence of the continuous-wave (cw) output power on the incident pump power of a-cut and c-cut Nd:GdVO₄ lasers. The pump threshold and the slope efficiency for the a-cut Nd:GdVO₄ laser were 0.5 W and 21.5%, respectively. While, for the c-cut Nd:GdVO₄ laser, the corresponding counterparts were 2.2 W and 31.4%, respectively. The higher threshold for the c-cut Nd:GdVO₄ laser operation was originated from its lower stimulated emission cross section. Also as shown in Fig. 2, in spite of its higher threshold, the c-cut Nd:GdVO₄ laser had a higher slope efficiency than the a-cut one, which showed that the c-cut Nd:GdVO₄ crystal had a lower intrinsic loss [17]. The high slope efficiency made it capable of producing higher output power than the a-cut laser under the same laser configuration and pump situation. Fig. 3 presents the power spectrum for the QML c-cut Nd:GdVO₄ laser. The dependence of the average output power for the c-cut and a-cut Nd:GdVO₄ lasers on the incident power is given in Fig. 4, the QML a-cut Nd:GdVO₄ laser began to operate when the pump power exceeded 2.25 W, a maximum average output power of 1.7 W was obtained at an incident pump power of 14.4 W. However, when the pump power was increased up

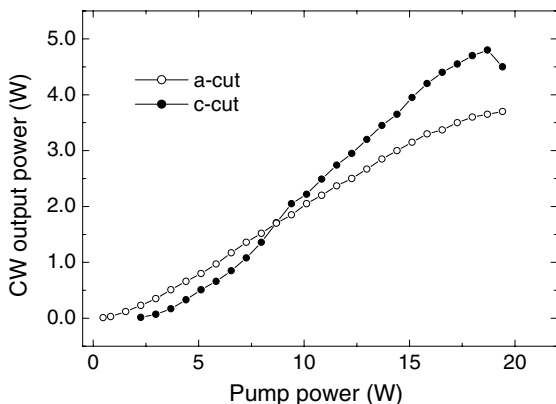


Fig. 2. Dependence of cw output power of the c-cut and a-cut Nd:GdVO₄ lasers on the incident laser power.

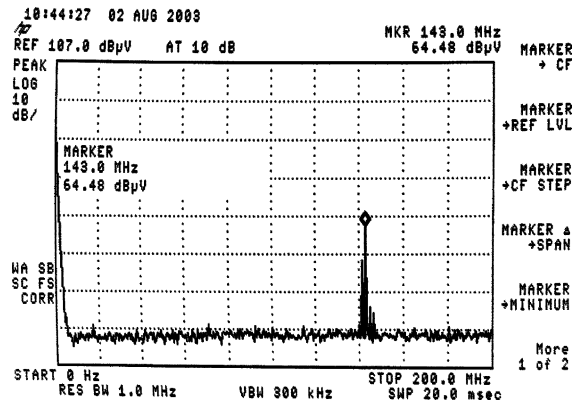


Fig. 3. The power spectrum for the QML c-cut Nd:GdVO₄ laser.

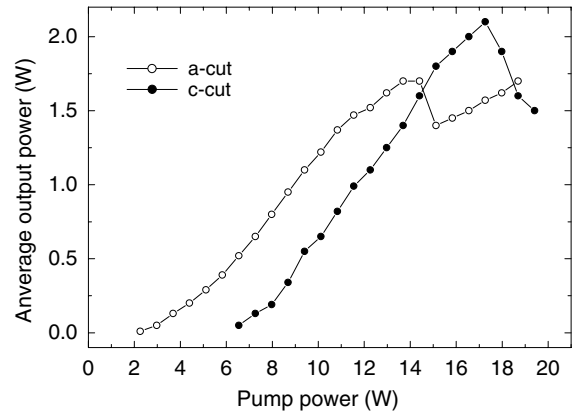


Fig. 4. The dependence of the average output power on the incident laser power for the QML c-cut and a-cut Nd:GdVO₄ lasers.

to 15.1 W, the QML operation turned into a cw one, and the output power decreased to 1.4 W, indicating that the Cr⁴⁺:YAG crystal was bleached. Increasing the pump power further, the cw output power increased from 1.4 to 1.7 W. As for the c-cut Nd:GdVO₄ laser, passive Q-switched mode-locking appeared at a pump power of 6.5 W and the average output power reached its maximum of 2.1 W when the incident pump power was 17.3 W. The average output power began to drop because of thermal-lens effect when the pump power exceeded 17.3 W, and the bleaching of the Cr⁴⁺:YAG crystal was not observed. The repetition rates of the Q-switched envelope for the c-cut and a-cut Nd:GdVO₄ lasers

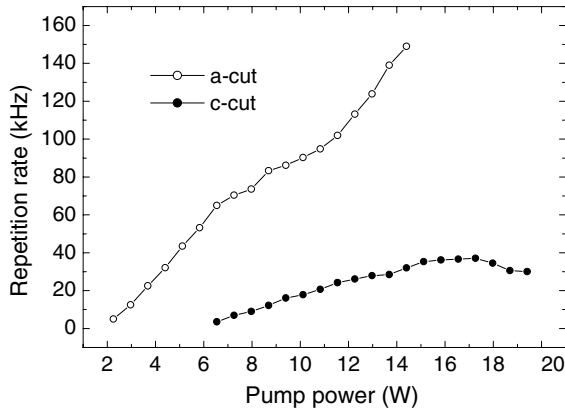


Fig. 5. The dependence of the Q-switched repetition rate on the incident laser power for the QML c-cut and a-cut Nd:GdVO₄ lasers.

are shown in Fig. 5. For the a-cut Nd:GdVO₄ laser, the repetition rate increased rapidly from 5 to 149 kHz when the pump power increased from 2.25 to 14.4 W, while for the c-cut Nd:GdVO₄ laser, it only increased from 3.52 to 37.0 kHz when the pump power increased from 6.5 to 17.2 W. The repetition rate of the Q-switched envelope for the c-cut Nd:GdVO₄ laser was much lower than that of the a-cut Nd:GdVO₄ laser. Consequently, the single Q-switched pulse energy for the c-cut Nd:GdVO₄ laser was much higher than that of the a-cut Nd:GdVO₄ laser, which is demonstrated in Fig. 6. Since the c-cut Nd:GdVO₄ has a lower stimulated emission

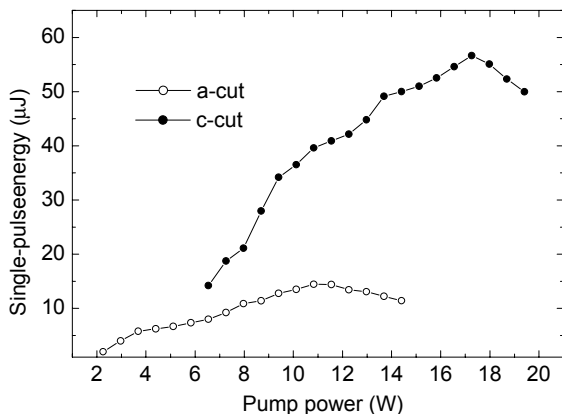


Fig. 6. The dependence of the single Q-switched pulse energy on the incident laser power for the QML c-cut and a-cut Nd:GdVO₄ lasers.

cross section, it can store more energy in the laser active material than the a-cut one under the same pump condition, which made the c-cut Nd:GdVO₄ laser capable of generating higher-energy Q-switched laser pulses with a lower repetition rate. As shown in Fig. 6, the maximum energy of a single Q-switched pulse for the a-cut Nd:GdVO₄ laser was 14.4 μJ. While for the c-cut one, the maximum energy of a single Q-switched pulse was 56.6 μJ, which was about four times higher than that obtained from the a-cut Nd:GdVO₄ laser. Due to the instability of the QML pulses, we did not measure the mode-locked pulse duration for the a-cut and c-cut Nd:GdVO₄ lasers. However, the mode-locked pulse duration was believed in the subnanosecond region as could deduce from the relaxation time of the ESA of Cr⁴⁺:YAG.

In conclusion, we demonstrated a passively QML c-cut Nd:GdVO₄ laser with an intracavity Cr⁴⁺:YAG saturable absorber. At a pump power of 17 W, a maximum average output power of the QML laser was 2.1 W with a Q-switched repetition rate of 37 kHz. The single Q-switched pulse energy was 56.6 μJ and the mode-locked pulse within the Q-switched envelope had a repetition rate of 143 MHz. The result in our work confirmed the excellent laser performance of c-cut Nd:GdVO₄ crystals for high-peak-power Q-switched and QML operation.

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