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Quasi-cw diode-pumped Nd:$GdVO_4$ laser passively Q-switched and mode-locked by Cr^{4+}:YAG saturable absorber

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Abstract

We report on the passively Q-switched mode-locking of a quasi-cw (QCW) diode pumped Nd:$GdVO_4$ laser with Cr^{4+}:YAG saturable absorber. We show that by using the QCW pumping high quality Q-switched mode-locking can be easily obtained in the laser even with a simple two-mirror laser cavity configuration. Mode locked pulses with pulse width of about 1 ps at repetition rate variable from 500 MHz to 1 GHz has been obtained.

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Keywords: Mode locking; Laser diodes; Solid-state lasers

1. Introduction

The Nd^{3+}-doped crystals due to their excellent lasing property and availability of direct laser diode pumping have been widely used for the diode pumped solid-state lasers. Apart from the traditional Nd:YAG and Nd:YVO_4 crystals, recently a new type of Nd^{3+}-doped vanadate crystal – Nd:$GdVO_4$ – has also attracted great attention. The Nd:$GdVO_4$ is an isomorph of Nd:YVO_4 crystal, however, compared with the Nd:YVO_4, it has even larger absorption cross-section and higher thermal conductivity along the ⟨1 0 0⟩ direction, which makes it promising even for the high power diode pumped solid-state lasers. Like Nd:YVO_4 crystal, Nd:$GdVO_4$ has a very large stimulated emission cross-section. A recent measurement showed that the stimulated emission

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cross-section of the Nd:$GdVO_4$ is in the range of 14.76×10^{-19}–16.4×10^{-19} cm^2, which is higher than that of the Nd:YVO_4 (12×10^{-19} cm^2) [1]. In addition, Nd:$GdVO_4$ crystals have a broad gain bandwidth of about 1.3 nm, which is broader than those of the Nd:YVO_4 (0.96 nm) and Nd:YAG (0.45 nm). This property of the Nd:$GdVO_4$ indicates that it has a potential to generate even narrower mode-locked pulses. Up to now, passive mode-locking of the diode-pumped Nd:$GdVO_4$ lasers has been demonstrated by several groups. Sorokin et al. [2] firstly reported the passive mode locking of the Nd:$GdVO_4$ laser. In their experiment, a mode-locked pulse width of 1.9 ps was achieved. Mode–locking of the laser with various solid-state saturable absorbers such as the saturable Bragg reflector (SBR) [3], semiconductor saturable absorber mirror (SESAM) [4,5] and GaAs wafer [6] was also reported.

The Cr^{4+}:YAG crystal is a well-known solid-state saturable absorber widely used for Q-switching the Nd^{3+}-doped solid-state lasers [7,8]. Cr^{4+}:YAG has a large saturable absorption cross-section in the 0.9–1.2 μm spectral region, high damage threshold and excellent thermal and optical properties. Passively Q-switched operation of the Nd:$GdVO_4$ lasers by using the Cr^{4+}:YAG as saturable absorber has also been reported [9,10]. A special property of the Cr^{4+}:YAG saturable absorber is that apart from the ground state absorption, it also has strong excited state absorption (ESA). Different to the ground state absorption, which has a recovery time of a few microseconds, ESA has a much shorter recovery time that is in the sub-nanosecond range [11]. This property of the Cr^{4+}:YAG saturable absorber makes that in the case of strong ground state absorption, Q-switched mode-locking could also appear in the passively Q-switched lasers. Q-switched mode locking of the diode-pumped Nd:YAG and Nd:YVO_4 lasers with Cr^{4+}:YAG saturable absorber has already been experimentally demonstrated [12–14]. Very recently, Zhang et al. [15] have also demonstrated the Q-switched mode-locking of a diode-pumped Nd:$GdVO_4$ laser with Cr^{4+}:YAG saturable absorber. As the ESA effect only takes place after that the ground state of the absorber is strongly saturated, for using the ESA to generate the passive mode locking, the laser beam intensity on the Cr^{4+}:YAG must be sufficiently strong. Therefore, a common characteristic of previous lasers with the Cr^{4+}:YAG to achieve the Q-switched mode-locking is that they have used a folded mirror cavity configuration, as with such a cavity configuration a relatively small beam spot on the Cr^{4+}:YAG crystal and a good mode matching between the laser mode and the pump beam can be simultaneously achieved. However, this laser cavity configuration is complicated in alignment and also difficult to easily change the mode-locked pulse repetition rate. In this paper, we report on a quasi-cw (QCW) diode pumped, passively Q-switched and mode-locked Nd:$GdVO_4$ laser with Cr^{4+}:YAG saturable absorber. We demonstrate experimentally that through using the QCW laser diode pumping, high quality Q-switched mode-locking with the Cr^{4+}:YAG crystal can be easily obtained even with a simple plane-parallel two-mirror laser cavity. By simply changing the cavity length, we further showed that the mode locked pulse repetition rate of our laser could be varied over a wide range from 500 MHz to 1 GHz. Mode-locked pulses with pulse width of about 1 ps have been obtained.

2. Experimental

A schematic diagram of the laser setup is shown in Fig. 1. A QCW fiber-coupled laser diode array

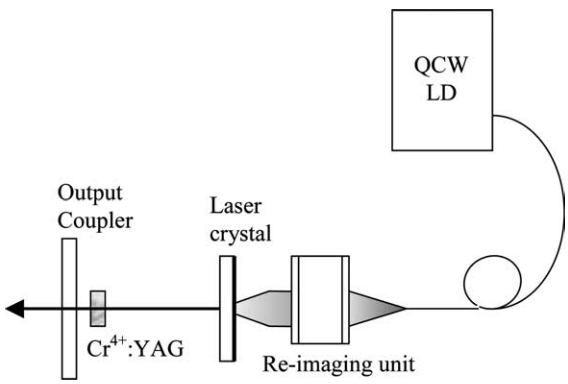

Fig. 1. Schematic of the experimental setup.

(Jenoptik, JOLD-120-QPXF-2P iTEC) was used as the pump source. The center emission wavelength of the laser diode array is 808 nm at 25 °C. The diode radiation from the 0.6 mm fiber bundle was focused into the laser crystal with an optical re-imaging system (Coherent, OIA 1:1.8). The pump beam in the crystal has a beam size of about 340 μm in diameter. An a-cut 0.5 at.% $Nd:GdVO_4$ crystal with a dimension of $3 \times 3 \times 6\ mm^3$ was used as the gain medium. One surface of the crystal is dichroically coated, anti-reflection (AR) at 808 nm and high reflection (HR) at 1064 nm, whereas the other surface of the crystal is AR coated at 1064 nm. The dichroically coated surface of the $Nd:GdVO_4$ crystal was also used as the input mirror of the laser cavity. The laser crystal was wrapped with a thin layer of indium foil and mounted in a water-cooled copper holder. A flat mirror with transmission of $T = 60\%$ at the 1064 nm was used as the output coupler of the laser cavity. The large output coupling was selected to possibly shorten the pulse build-up time in the cavity as it was shown that a short pulse build-up time is beneficial to the passive laser mode-locking process [16]. Two ⟨1 1 1⟩-cut Cr^{4+}:YAG absorbers with initial transmission of 50% and 40% were used in the experiment. The dimensions of the Cr^{4+}:YAG crystals are $5 \times 5 \times 3.7\ mm^3$ and ϕ 8 mm × 1.55 mm, respectively.

In our experiments, the operation of the QCW diode laser was set at 100 μs pulse duration, 1% pulse duty cycle and pulse repetition rate of 100 Hz. We first studied the free running of the laser. Fig. 2 shows the free-running laser output energy with respect to the pump energy at two different laser cavity lengths, detected with a pyroelectric head energy meter (Ophir, Pin 1Z02128, PE50-SH). Despite of the fact that the laser design was not optimized, the slope efficiency of the laser at the two cavity lengths could still be as high as 50%, which is comparable to those reported for the CW laser diode end-pumped $Nd:GdVO_4$ lasers. When the cavity length was set at 150 mm, the output energy increased linearly with the pump energy, and the maximum output energy of 4.3 mJ was obtained at the maximum available pump energy of 12 mJ. While when the cavity length was set at 285 mm, as the pump energy increased beyond

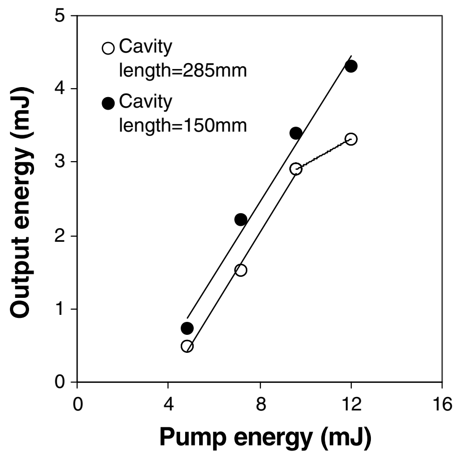

Fig. 2. Output energy versus pump energy for the free running laser at the cavity length of 285 mm.

9.6 mJ, the output energy exhibited a tendency of saturation. As there is no such tendency at the short cavity length, we believe it could be caused by the thermal lens induced cavity diffraction loss. The laser cavity is practically stabilized by the thermal lens formed in the crystal, which also causes laser beam wave front distortions and diffraction losses of the cavity. In the case of long cavity length, the impact of this thermal lens induced cavity diffraction loss on the laser performance could become significant.

We then inserted the Cr^{4+}:YAG crystal into the laser resonator at a location 10 mm away to the output coupler. With a Cr^{4+}:YAG saturable absorber in cavity, the passively Q-switched and mode-locked (QML) pulses were immediately obtained, even at the Q-switching threshold of the laser. Fig. 3 shows for example, the typical QML pulses of the laser obtained with the cavity length of 285 mm, pump energy of 12 mJ and Cr^{4+}:YAG initial transmission of $T_0 = 50\%$ and $T_0 = 40\%$, respectively. Under the condition the passively Q-switched pulses have a pulse width of 33 ns (Fig. 3(a)) and 30.4 ns (Fig. 3(b)) for each of the two saturable absorbers. As shown in Fig. 3, the Q-switched pulses were fully modulated by the mode locked pulses with a repetition rate of about 500 MHz, which corresponds well to the cavity axial mode interval. Based on the experimentally measured

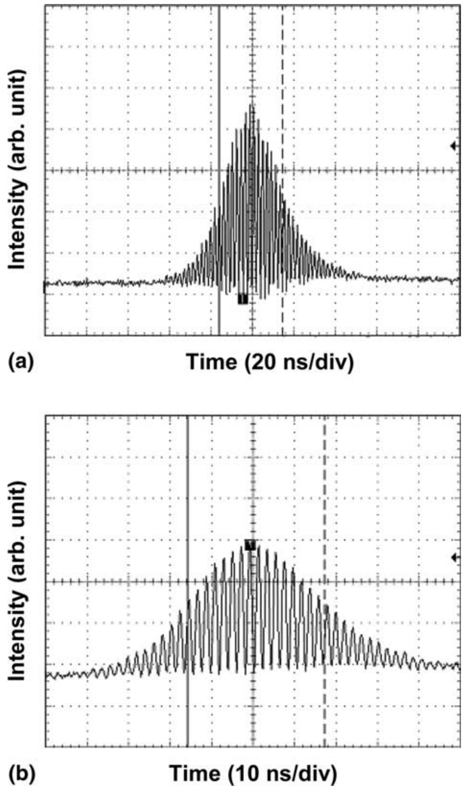

Fig. 3. Typical QML pulses obtained with Cr^{4+}:YAG of (a) $T_0 = 40\%$, (b) $T_0 = 50\%$ under the cavity length of 285 mm and the pumping energy of 12 mJ.

output energy of the laser at the Q-switching threshold and the calculated cavity mode size, we have estimated the laser energy fluence in the Cr^{4+}:YAG crystal, which is about 30 mJ/cm^2. If taking the ESA cross-section of the Cr^{4+}:YAG as $\sigma_{esa} = 2 \times 10^{-18}$ cm^2 [17], its saturation fluence is calculated as 47 mJ/cm^2, which is comparable to the experimentally measured value.

We have also investigated the influence of the effective mode size at the absorber on the mode-locked operation. To this end, we changed the positions of the Cr^{4+}:YAG in the resonator in the range from 10 to 100 mm away to the output mirror. Even operating at the Q-switching threshold, there was no any significant change either to the Q-switched pulses or to the modulation depth of the QML pulses as observed in the laser. We attribute this as a result of too strong intracavity laser energy fluence in the Cr^{4+}:YAG crystal, which is simply always above the QML threshold. Although high quality mode-locking was obtained for each of the Q-switched pulses at the cavity length, the Q-switched pulses were very unstable, their pulse energy and repetition rate jittering can be as large as more than 30% as detected with a high-speed photoreceiver (New Focus, 1611-FS; rise time: 350 ps). Fig. 4 shows the total energy of the laser output and the average Q-switched pulse width under each of the Cr^{4+}:YAG saturable absorbers. The average Q-switched pulse width decreased with the increase of the pump energy. With the strong saturable absorber ($T_0 = 40\%$) in cavity, generally a slightly narrower Q-switched pulse was always obtained than that with a weaker saturable absorber. From Fig. 4, it can be seen that while with the stronger absorber ($T_0 = 40\%$) in cavity the total laser output shows a linearly increase with the pump energy, there is a clear total output energy drop at the maximum pump energy of 12 mJ with the weaker absorber ($T_0 = 50\%$) in cavity. A similar laser output energy decline was also observed in the free running case. Therefore, we attribute it again as caused by the thermal lens induced cavity diffract losses. As under existence of strong saturable absorption the relative influence of the cavity diffraction losses on the laser operation becomes less obvious, consequently, the

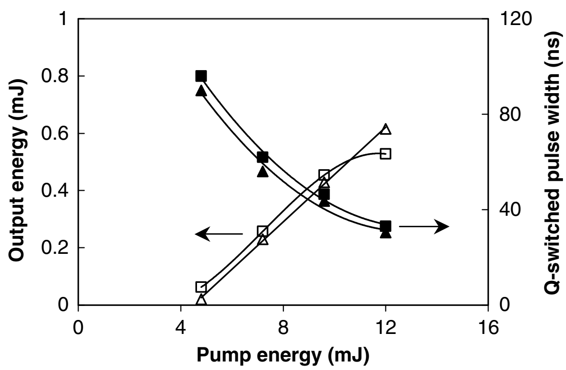

Fig. 4. Average energy of the laser output (primary axis) and the Q-switched pulse width (secondary axis) with the pump energy. Triangle: Cr^{4+}:YAG initial transmission $T_0 = 40\%$; Square: Cr^{4+}:YAG initial transmission $T_0 = 50\%$.

output energy drop would only appear at an even higher pump power.

An advantage of using the simple two-mirror cavity configuration is that through changing the cavity length, the mode-locked pulse repetition rate can be easily varied. We therefore varied the cavity length from 285 to 150 mm to shift the mode locked pulse repetition rate from the 500 MHz to 1 GHz. We found experimentally that with such a short cavity length, where the position of saturable absorber was remained at 10 mm away from the output coupler, Q-switched mode-locking can still be obtained. Fig. 5 shows for example a typical Q-switched and mode-locked pulse profile obtained at this cavity length with the pump energy of 4.8 mJ. In comparison with the Q-switched mode-locking obtained at a longer cavity length, where high quality Q-switched mode-locking was always obtained, the Q-switched mode-locking obtained at the short cavity length occasionally shows only partial mode-locking modulations, which indicates that the mode locking quality was degraded with the reduction of the laser cavity length. Fig. 6 shows the measured Q-switched pulse properties at the short cavity length. Compared with Fig. 4, even narrower Q-switched pulses and larger total laser output energy could be obtained under the same pump energy.

We believe that the observed dependence of the mode-locking property to the cavity length may be caused by the laser beam size change on the saturable absorber. Considering the existence of the thermal lens effect in the gain medium, with a long laser cavity the laser beam size on the saturable absorber is smaller, consequently, the ESA effect is stronger, which enhances the mode-locking effect. In contrast, with a short laser cavity, the effective laser beam size on the Cr^{4+}:YAG crystal becomes larger, and hence at the same pump energy level the ESA effect will become weaker, which consequently leads to poorer mode-locking performance.

Using a commercial autocorrelator (Femtochrome, FR-103XL) we have also measured the QML pulse width of the lasers. Fig. 7 shows a

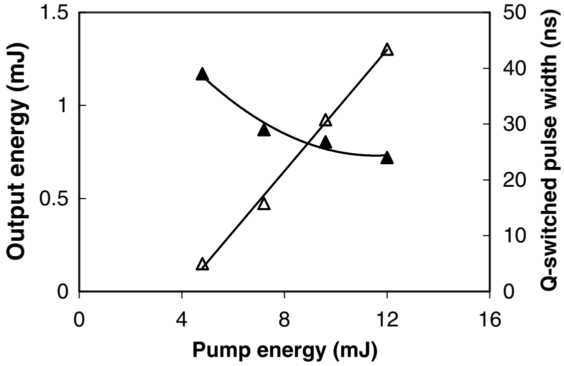

Fig. 6. Average energy of the laser output (primary axis) and the Q-switched pulse width (secondary axis) with the pump energy obtained at the short cavity of 150 mm.

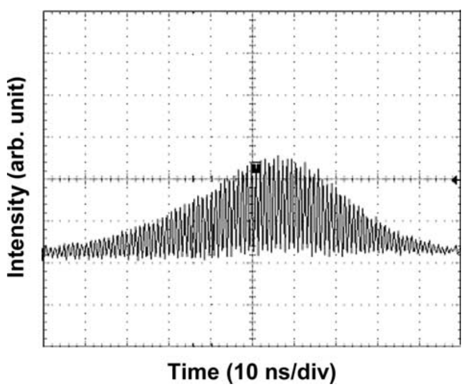

Fig. 5. A typical QML pulse obtained at the cavity length of 150 mm and pumping energy of 4.8 mJ. The Cr^{4+}:YAG of $T_0 = 40\%$ was used.

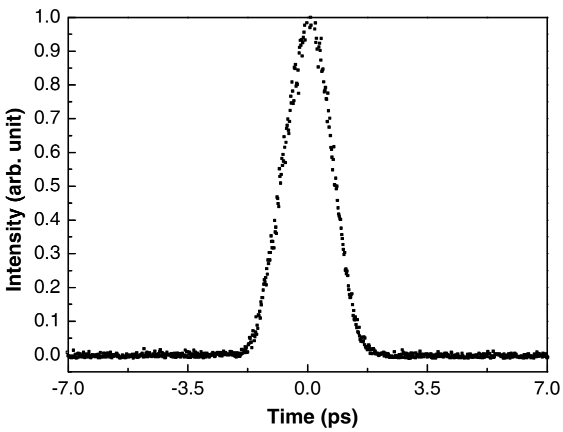

Fig. 7. Autocorrelation trace of the QML laser pulses.

measured autocorrelation trace. The autocorrelation trace has a pulse width (FWHM) of about 1.5 ps, if the mode-locked pulses are assumed to have a hyperbolic secant pulse profile, the mode-locked pulse width is estimated as about 0.97 ps. This measured pulse width is close to that of the transform-limited pulse determined by the $Nd:GdVO_4$ gain bandwidth, which is about 0.9 ps. Although, the ESA absorption of the Cr^{4+}:YAG crystal only has a recovery time of about 0.1 ns [17], surprisingly, the mode-locked pulse width obtained in our experiment could be substantially narrower than it. What could be the mechanism and whether it is caused by any nonlinear effect of the $Nd:GdVO_4$ crystal or the Cr^{4+}:YAG crystal need to be further investigated.

3. Conclusions

In conclusion, we have experimentally demonstrated passively Q-switched mode-locking in a QCW laser diode pumped $Nd:GdVO_4$ laser with Cr^{4+}:YAG saturable absorbers. We found that by using the QCW pumping, high quality Q-switched mode-locking can be easily obtained in the laser even with a simple two-mirror laser cavity configuration. Mode-locked pulses with pulse width of about 0.97 ps and variable repetition rate from 500 MHz to 1 GHz have been obtained. The advantage of using QCW pumping compared with the CW laser diode pumping is that high peak pump power could be easily generated, which facilitates strong ESA in the Cr^{4+}:YAG saturable absorber and hence results in the Q-switched mode-locking.

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