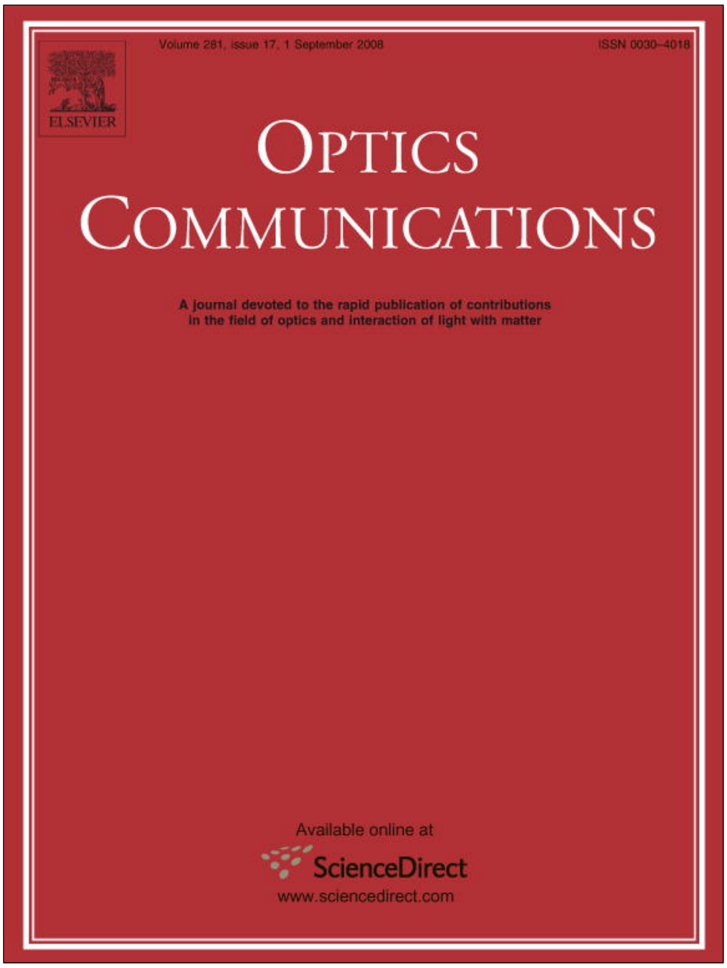
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Diode-pumped passively mode-locked $Nd:GdVO_4$ laser at 912 nm

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ABSTRACT

We have demonstrated the stable mode-locked $Nd:GdVO_4$ laser operating on the $^4F_{3/2}$–$^4I_{9/2}$ transition at 912 nm. With a four-mirror-folded cavity and a semiconductor saturable absorber mirror for passive mode-locking, we have gained 6.5 ps laser pulses at a repetition rate of 178 MHz. The laser is diode-end-pumped, and the total output power from the out coupler is 128 mw at an incident pump power of 19.7 W.

During the past decades, the $^4F_{3/2}$–$^4I_{9/2}$ transition of Nd^{3+} has been investigated intensively, for its applications in many fields, such as displaying, water vapor detecting, medical treatment, and scientific research. Up to now, to our knowledge, The CW mode-locked laser operating on the $^4F_{3/2}$–$^4I_{9/2}$ transition of Nd^{3+} doped in different kinds of hosts have been demonstrated and pulses as short as 1.9 ps for $Nd:YAlO_3$ at 930 nm [1], 8.8 ps [2] and 3 ps [3] for $Nd:YVO_4$ at 914 nm have been produced. $Nd:GdVO_4$ crystal was first introduced as a laser crystal by Zagumennyi et al. in 1992 [4]. Many experiments carried out to investigate this crystal has shown that $Nd:GdVO_4$ is an excellent crystal suited for diode pumping [5–8]. $Nd:GdVO_4$ possesses higher thermal conductivity, a larger absorption cross-section, and a larger stimulated emission cross-section compared to $Nd:YVO_4$, $Nd:YAlO_3$, and Nd:YAG [9]. In addition, $Nd:GdVO_4$ emits the shortest-wavelength radiation on the $^4F_{3/2}$–$^4I_{9/2}$ transition for its smallest splitting (409 cm^{-1}) of the lower laser level. However, it puts this quasi-three-level laser operating at a disadvantage, because the lower laser level is the upper sub-level of the $^4I_{9/2}$ multiplet, this sub-level is thermally coupled with the ground-state and should be efficiently populated with increasing temperature. This would cause an increase in the ground-state absorption loss, an increase in passive intra-cavity loss, an increase in the laser threshold and reducing the output energy of the laser. Last year, our group successfully demonstrated the CW passively mode-locked $Nd:GdVO_4$ laser at 912 nm. Unfortunately, the total output power is as low as 22.6 mw, and the pulse width was not measured for the low output [10]. In this letter, we present a stable CW mode-locked $Nd:GdVO_4$ laser at 912 nm with the total output of 128 mw and the pulse width of 6.5 ps.

The schematic diagram of the system is shown in Fig. 1. We employed a four-mirror folded cavity, the total physical length of the cavity is approximately 827 mm. The pump source is a commercially available fiber-coupled diode-laser which could emit a rated maximum power of 30 W at 808 nm, with a core diameter of 200 μm and a N.A. of 0.22. The circular spot was imaged into the crystal with a coupling system (Limo GmbH, Germany), which is with a magnification of 1:1. The waist of the pump laser in the crystal is about 200 μm. The dimensions of the crystal are $3 \times 3 \times 4\ mm^3$ with a concentration of 0.2 at%. One facet of the crystal which acted as an end mirror is coated for antireflection (AR) at 808 nm and 1064 nm and 1340 nm and for high reflection (HR) at 912 nm, and the other facet is coated AR at 912 nm, 1064 nm and 1340 nm. The crystal is wrapped with indium foil and then mounted in a water-cooled copper block. The water temperature was maintained at 10 °C. The SESAM (Batop GmbH, Germany) used for mode-locking is with a modulation depth of 2% at 912 nm and a saturation fluence of 70 $\mu J/cm^2$ [11–13], it is mounted on a small copper heat sink so that the loaded heat can be easily removed.

As a preliminary experiment, we tested the performance of the $Nd:GdVO_4$ 912 nm laser in CW operation pumped by the diode laser. A plane mirror coated HR at 912 nm replaced the SESAM, and then the laser was operating at 912 nm. Fig. 2 shows the dependence of the CW output on the incident pump power. The CW

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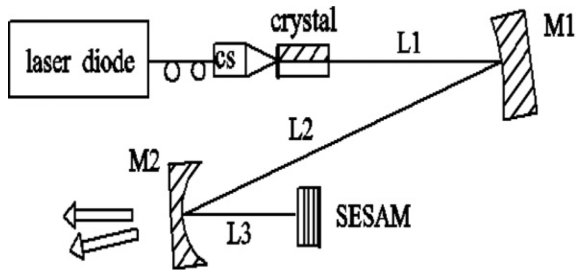

Fig. 1. Experimental layout of passively mode-locked $Nd:GdVO_4$ laser. M1: HR at 912 nm, radius of curvature (RoC) is 300 mm; M2: I = 1 % at 912 nm, radius of curvature (RoC) is 100 mm; CS: coupling system; L1: 260 mm, L2: 500 mm, L3: 67 mm.

output is the total of the two beams from the output coupler M2, and the maximum output power of 1.45 W was obtained with an incident pump power of 20.3 W. Compared to the laser which had a maximum output of 2.1 W with an incident pump power of 16.7 W, previously reported by Czeranowsky et al. [14], our result was weaker. After the configurations of the two lasers are analyzed, we see the longer length of the crystal, the higher Nd^{3+} doped concentration and the smaller pump waist in the crystal configured in our experiment than those in Czeranowsky's. These factors may lead to higher absolute temperature and a bigger temperature gradient in the crystal, so the re-absorption loss due to the thermal population of the lower laser level is relatively increased and the output power is relatively lowered. Besides, the output power decreases with the increase of the pump power when the pump power beyond the 20.3 W, which is believed that the re-absorption loss is the main reason. Moreover, this can also be due to the effect of the thermal gradient on the laser stability because of the thermal lens.

Then we put the SESAM instead of the plane mirror in the cavity. The dependence of the total power of the two output beams on incident pump power is shown in Fig. 1 together with the CW output. The huge difference between the CW output and the mode-locked output indicates a high unalterable loss of the SESAM [15]. The threshold pump power is 9.67 W. The laser operates in Q-switched mode-locking region at a pump power range of $9.67\ \mathrm{W} \leqslant P_{pump} \leqslant 12.37\ \mathrm{W}$. At higher pump power, a stable CW mode-locking state was observed. The waveform of CW mode-locked pulse trains detected with a fast photodiode is shown in Fig. 3. The repetition rate was 178 MHz and the maximum output power was 128 mw at a pump power of 19.7 W.

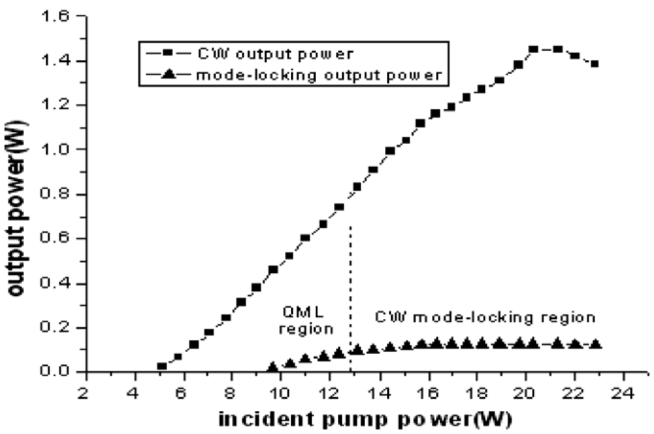

Fig. 2. Dependence of the laser CW output and mode-locking output on the incident pump power. ■ and ▲ indicate the CW output power and mode-locking output power, respectively. QML: Q-switched mode-locking.

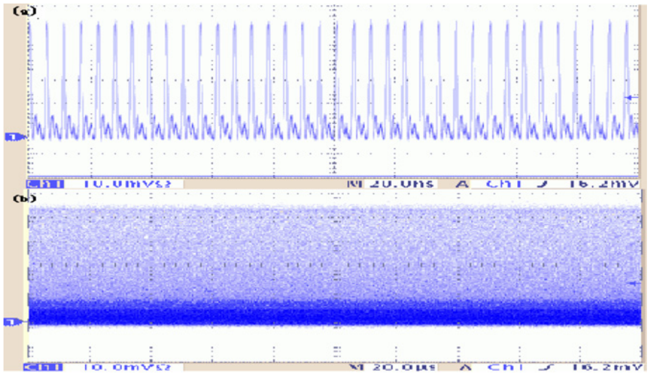

Fig. 3. Pulse trains observed with two different time scales: (a) 20 ns and (b) 20 us.

The pulse width was measured with a homemade non-collinear second-harmonic-generation auto-correlator. The trace of the SHG autocorrelation is shown in Fig. 4. Assuming a Gaussian pulse profile, we estimated the pulse duration to be approximately 6.5 ps. The corresponding spectrum is shown in Fig. 5, it has two peaks at the central wavelengths of 912.3 nm and 912.7 nm, respectively, with the resolution limit of the spectrometer, we judge the both

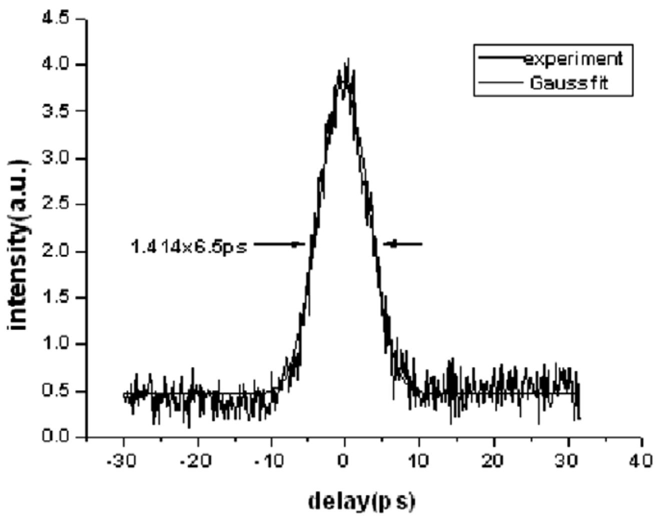

Fig. 4. The measured autocorrelation trace of the pulses.

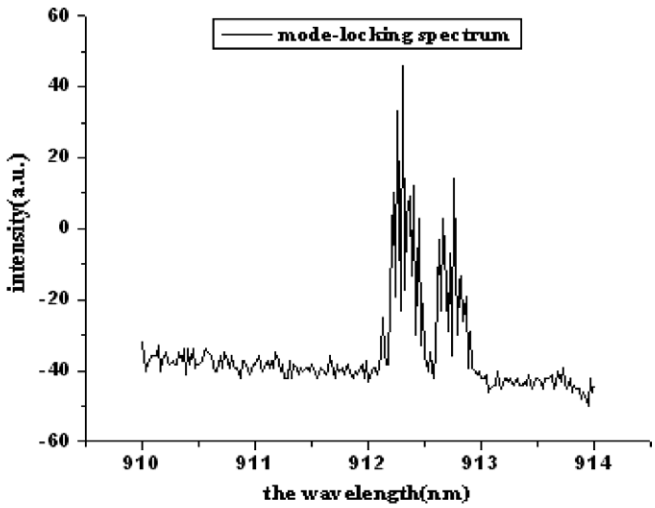

Fig. 5. The corresponding mode-locking spectrum.

corresponding bandwidths are 0.25 nm (FWHM). Meanwhile, the 1064 nm wavelength was completely suppressed.

In conclusion, we have demonstrated a diode-pumped passively CW mode-locked Nd:$GdVO_4$ laser at 912 nm. With a four-mirror-folded cavity and a semiconductor saturable absorber mirror for passive mode-locking, we have gained 6.5 ps laser pulses at 178 MHz repetition rate. The output power is 128 mw at a pump power of 19.7 W. when a SESAM with a lower unsaturable loss is used, and/or the waist of the pump beam in the crystal is appropriately enlarged under the condition that the laser mode matches the pump mode, a more efficient and more robust mode-locked Nd:$GdVO_4$ laser at 912 nm is worth looking forward to.

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