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Passively mode-locked Nd:$GdVO_4$ laser at 912 nm*

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This paper demonstrates the passively mode-locked Nd:$GdVO_4$ laser operating on the $^4F_{3/2}$–$^4I_{9/2}$ transition at 912 nm by using a semiconductor saturable-absorber mirror for passive mode locking, stable continuous wave mode-locked 912 nm laser was achieved with a repetition rate of 176 MHz. At the incident pump power of 17.7 W, 22.6 mW average output power of stable mode-locked laser was obtained with a slope efficiency of 0.3%.

Keywords: diode-pumped laser, solid-state laser, mode locking

PACC: 4255, 4260,4270

Over the past few years, diode end-pumped passively mode-locked solid-state lasers with semiconductor saturable-absorber mirror (SESAM) have attracted significant interest because of their short pulse duration, low cost, and reliable operation.[1–4] The passively mode-locked Nd-doped lasers operating at the $^4F_{3/2}$–$^4I_{9/2}$ transition have attracted much attention mainly for generation of blue laser by means of frequency doubling. However, these kinds of mode-locked lasers are difficult to obtain because of the considerable re-absorption loss and the small emission cross-section of the laser operating at quasi-three level system. Last year, a passively mode-locked Nd:YVO_4 laser operating at 914 nm was successfully realized by Schlatter *et al*[5] by using a standard delta cavity with a Ti:sapphire pump laser. The average output power of 42 mW was obtained with 3 ps pulses at a repetition rate of 233.8 MHz. This year, a diode-pumped passively mode-locked Nd:YVO_4 laser at 914 nm was reported by Blandin *et al.*[6] They achieved 87 mW average output power with 8.8 ps pulses at a repetition rate of 94 MHz. Besides Nd:YVO_4 crystal, another member from the vanadate family, Nd:$GdVO_4$, is another excellent laser crystal. This crystal has all the advantages of Nd:YVO_4 crystal (for example, it has large absorption and emission cross-sections and the output laser is linearly polarized). Moreover, the advantage of Nd:$GdVO_4$ crystal in comparison with Nd:YVO_4 crystal is the high heat conduction in the < 110 > direction which is comparable with that of Nd:YAG crystal. However, it is a pity that the crystal field splitting of 409 cm^{-1} in Nd:$GdVO_4$ is smaller than that in Nd:YVO_4 (433 cm^{-1}),[7,8] so the Boltzmann factor of the lower laser level in Nd:$GdVO_4$ crystal is larger than that in Nd:YVO_4 crystal. So the laser operating at quasi-three level system in Nd:$GdVO_4$ crystal is more difficult to realize than that in Nd:YVO_4 crystal because we have to overcome high re-absorption loss in Nd:$GdVO_4$ crystal. In this paper, we demonstrate the mode-locked Nd:$GdVO_4$ laser operating on the $^4F_{3/2}-{}^4I_{9/2}$ transition at 912 nm for the first time. By using a SESAM for passive mode locking, stable continuous wave (CW) mode-locked 912 nm laser was achieved with a repetition rate of 176 MHz. At the incident pump power of 17.7 W, we obtained 22.6 mW average output power of stable mode-locked laser with a slope efficiency of 0.3%.

The schematic diagram of the laser configuration is shown in Fig.1.

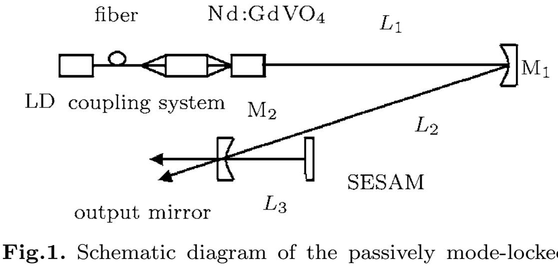

Fig.1. Schematic diagram of the passively mode-locked 912 nm Nd:$GdVO_4$ laser.

The pump source was high-brightness fibre-coupled

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diode laser emitting at 808 nm. The pump power from the fibre with a core diameter of 200 μm and a numerical aperture of 0.22 was coupled into the gain medium by the coupling system. The $Nd:GdVO_4$ crystal had 0.2 at% Nd^{3+} concentration and dimensions of 3 mm × 3 mm × 4 mm. The end surfaces of the $Nd:GdVO_4$ crystal were polished with a high accuracy to obtain parallel flat surfaces. The laser crystal was mounted in a water-cooled heat sink (T = 10°C). For simplicity and reduction of cavity loss, the pump facet of the $Nd:GdVO_4$ crystal served as one of the resonator mirrors and was coated for antireflection (AR) at 808 nm and high reflection (HR) at 912 nm. High transmission at 1.06 μm and 1.34 μm was also specified to suppress parasitic oscillation at these wavelengths. The other end of the laser crystal was AR coated at 1.06 μm, 1.34 μm and 912 nm. M_1 was the folded mirror which was coated for HR at 912 nm with 300 mm radius of curvature. M_2 was the output coupler with 0.6% transmission at 912 nm with 100 mm radius of curvature. The arm lengths of three branches, L_1, L_2, and L_3, were approximately 23.9 cm, 54.7 cm and 6.5 cm respectively, thus the total cavity length should be 85.1 cm. In order to get mode-locked laser pulses, we put a SESAM in the cavity. Unfortunately, the SESAM that was designed for mode locking at 912 nm was not available up to now. We chose a commercially available SESAM. But this SESAM was designed for mode locking at 940 nm with a high-reflection band (R > 99%) from 920 nm to 990 nm. The optical efficiency of the mode-locked laser would be low because 912 nm was in the edge of the high-reflection band. The laser mode radii were estimated to be about 50 μm on the SESAM and 90 μm inside the $Nd:GdVO_4$ crystal.

Figure 2 shows the average output power as a function of the incident pump power. The oscillation threshold of 912 nm was 9.6 W. Within the range of the incident pump power from 9.6 to 16.1 W, we obtained the Q-switched and mode-locked laser pulses. When the incident pump power was greater than 16.1 W, the laser exhibited stable CW mode-locked operation with a repetition rate of 176 MHz. Figure 3 shows the spectrum of mode-locked 912 nm laser which was detected by using the high-resolution spectrometer. The CW mode-locked pulse train was monitored by a fast response photodiode and a 500 MHz oscilloscope. The result is shown in Fig.4. We obtained 22.6 mW average output power of CW mode-locked 912 nm laser at the incident pump power of 17.7 W with a slope efficiency of 0.3%. Because the average output power of the mode-locked laser was so small, we could not measure the pulse width of the mode-locked laser.

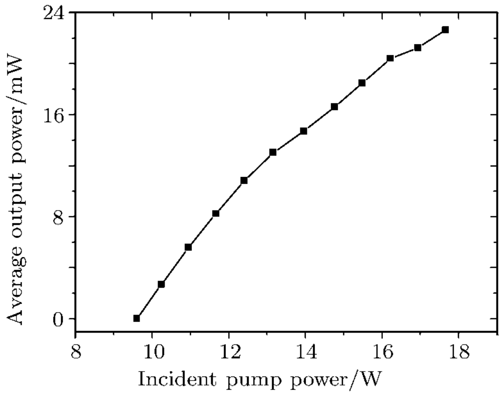

Fig.2. The average output power of 912 nm mode-locked laser as a function of the incident power.

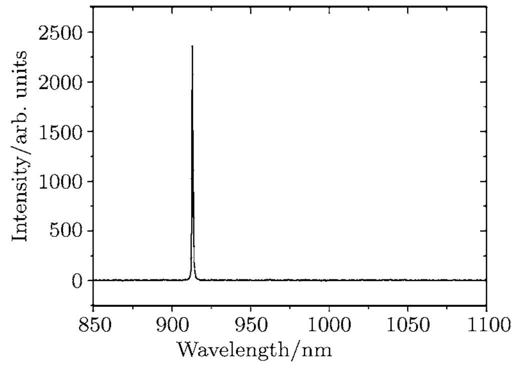

Fig.3. The spectrum of 912 nm mode-locked laser.

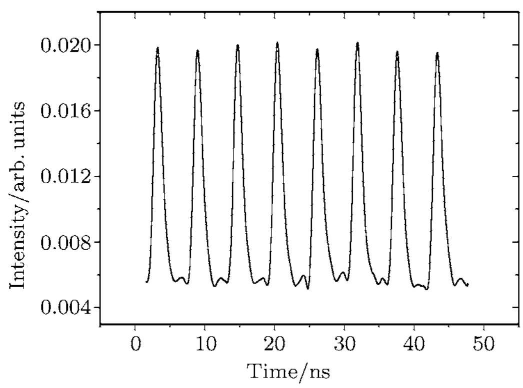

Fig.4. Pulse train of the 912 nm CW mode-locked $Nd:GdVO_4$ laser.

In conclusion, we have demonstrated the mode-locked $Nd:GdVO_4$ laser operating on the ${}^4F_{3/2}$–${}^4I_{9/2}$ transition at 912 nm for the first time. By using a SESAM for passive mode locking, stable CW mode-locked 912 nm laser was achieved with a repetition rate of 176 MHz. At the incident pump power of 17.7 W, we obtained 22.6 mW average output power of stable mode-locked laser with a slope efficiency of 0.3%. Because the SESAM used in our experiment was not designed for 912 nm, the small average output power of the mode-locked laser with low optical efficiency was obtained. Therefore, we could not measure the pulse width of the mode-locked laser. We look forward to performing future work with better-adapted SESAMs, which would offer better laser stability, robustness, and efficiency.

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