

Comparative studies of passively mode-locked Nd:Gd_{0.64}Y_{0.36}VO₄ laser and Nd:GdVO₄ laser with semiconductor saturable absorber mirrors

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We report on the continuous-wave mode locking of a diode-pumped Nd:Gd_{0.64}Y_{0.36}VO₄ laser with a semiconductor saturable absorber mirror (SESAM). By using SESAM method, mode-locked pulses as short as 7.1 ps, with a peak power of 2.4 kW and repetition rate of 55.6 MHz, were generated. Comparative studies between the passive mode-locking of the Nd:Gd_{0.64}Y_{0.36}VO₄ laser and the Nd:GdVO₄ laser were carried out.

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1. Introduction

The zircon structure neodymium-doped vanadate crystal Nd:YVO₄, with a large emission cross-section at around 1064 nm and a high absorption coefficient at 808-nm band, has been proved to be an excellent solid-state laser gain medium [1]. In recent years, the Nd³⁺-doped GdVO₄ crystal, which is an isomorph of Nd:YVO₄ crystal, has also attracted considerable attention as a novel diode-pumped solid-state laser material [2]. In comparison with the Nd:YVO₄ crystal, Nd:GdVO₄ has even higher absorption coefficient and larger emission cross-section [3]. It also has excellent thermal conductivity along the {110} direction, which is about two times larger than that of the Nd:YVO₄ [2]. Therefore, the Nd:GdVO₄ is more suitable to be used in the high power diode-pumped solid-state lasers. Furthermore, because of the large stimulated emission cross-section of the Nd:GdVO₄ crystal, continuous-wave (CW) mode-locking of this type of lasers can be easily achieved with semiconductor saturable absorber mirrors (SESAMs). Up to now, the passively mode-locked Nd:GdVO₄ lasers have been extensively investigated. The first diode-pumped passively mode-locked Nd:GdVO₄ laser, delivering 1.9 ps pulses, was reported by E. Sorokin *et al.* in 1993 [4]. Recently, passively CW mode-locked Nd:GdVO₄ lasers either with a saturable Bragg reflector (SBR) or with a SESAM were demonstrated [5, 6], with the mode-locked pulse width of 9.2-ps and 8-ps, respectively. In addition to the CW mode-locking, Q-switched mode-locking in Nd:GdVO₄ lasers by using SESAM or the Cr⁴⁺:YAG single crystal as saturable absorbers has also been investigated. It was found that the

Nd:GdVO₄ laser can be well operated in the Q-switched mode-locking state [7,8], especially when the c-cut Nd:GdVO₄ single crystal was utilized in the laser system [9].

Very recently, a new class of mixed vanadate crystals were developed by fractionally replacing the Y ions in the Nd:YVO₄ crystal with the Gd ions. It was found that these new neodymium doped vanadate crystals (Nd:Gd_xY_{1-x}VO₄) not only inherit the combined general properties of the Nd:YVO₄ and the Nd:GdVO₄ crystals, but also possess some new features [10]. As the Y and Gd ions are now randomly distributed in the lattice, which modifies the local crystal field experienced by the Nd ions, these new vanadate crystals have therefore a inhomogeneously broadened gain profile with bandwidth broader than those of the Nd:YVO₄ and Nd:GdVO₄ crystals. Fig. 1 shows for example the comparison between the fluorescence spectra of a 0.5 at. % doping Nd:Gd_{0.64}Y_{0.36}VO₄ crystal sample and the same doping Nd:GdVO₄ single crystal measured with an optical spectrum analyzer (ANDO 6315B). Due to the different host materials, their emission peaks are slightly different. One is centered at 1063.7 nm (Nd:Gd_{0.64}Y_{0.36}VO₄) and the other at 1063.3 nm (Nd:GdVO₄). The spectral bandwidth of the Nd:Gd_{0.64}Y_{0.36}VO₄ sample is around 1.3 nm, while that of the Nd:GdVO₄ sample is about 1 nm. It is worth mentioning that even larger fluorescence bandwidth of the mixed crystals can be obtained by further changing the fractions of the Y ions and Gd ions. The maximum bandwidth so far achieved is about 2 nm [11, 12]. Indeed,

previous experimental results have shown that with the broadened gain bandwidth, even shorter mode-locked pulses could be obtained in the Nd:Gd_{0.64}Y_{0.36}VO₄ lasers than in the Nd:GdVO₄ lasers. For instance, mode-locked pulses with 8.8-ps pulse duration were obtained in a passively CW mode-locked Nd:Gd_{0.64}Y_{0.36}VO₄ laser with a GaAs single crystal wafer as saturable absorber as well as the output coupler [13]. The pulse width is much shorter than those achieved in the mode-locked Nd:GdVO₄ laser (19 ps) and Nd:YVO₄ laser (31 ps) by using the same type of GaAs wafers as saturable absorbers [14, 15]. However, comparing with other semiconductor saturable absorbers such as SBR and SESAM, the GaAs has a strong slow saturable absorption on the 1- μ m band photon and usually introduces the Q-switching instability in the mode-locked laser, which is undesirable for many applications where a constant pulse energy and high repetition rate are needed.

In this paper we report on the continuous-wave mode locking of a diode-pumped Nd:Gd_{0.64}Y_{0.36}VO₄ laser with a semiconductor saturable absorber mirror (SESAM). By using the SESAM method, the continuous-wave mode-locked pulses as short as 7.1 ps were generated. An average output power of 0.93 W was obtained with a 9-W incident pump power. The repetition rate of the mode-locked pulses was 55.6 MHz, which gives a peak power as high as 2.4 kW. Comparative studies between the mode-locked Nd:Gd_{0.64}Y_{0.36}VO₄ laser and Nd:GdVO₄ laser were also carried out.

2. Experimental setup and results

The Nd:Gd_{0.64}Y_{0.36}VO₄ sample used in the experiments is a-cut. It has a Nd³⁺-doping concentration of 0.5 at.% and a dimension of 3.5×3.5 mm in cross-section and 5 mm in length. Both sides of the crystal sample are anti-reflection (AR) coated at 1064 nm. The a-cut Nd:GdVO₄ single crystal used for comparison also has a 0.5 at.% Nd³⁺-doping concentration, and the same dimensions and coatings. The same cavity design was used since both crystals have similar physical and optical properties. To realize CW mode-locking, a narrow beam waist inside the saturable absorber is preferred [16, 17]. Therefore, the laser cavity was so designed that the mode size in the gain medium matches the pump beam size, and simultaneously it is as small as possible in the saturable absorber. Since the pump-induced thermal lens effect in the gain medium can strongly affect the laser performance through changing the cavity stability condition and mode size [18], the thermal focal lengths formed in Nd:Gd_{0.64}Y_{0.36}VO₄ under various pump power levels were investigated. It was found that Nd:Gd_{0.64}Y_{0.36}VO₄ exhibits a weaker thermal lens effect than the pure Nd:GdVO₄ crystal does. When the pump power increased from 6 Watts to 13 Watts, the thermal focal lengths decreased from 600 mm to 250 mm for the Nd:Gd_{0.64}Y_{0.36}VO₄ crystal, and from 450 mm to 180 mm for the Nd:GdVO₄ crystal. Based on the measured thermal focal lengths, the laser cavity was constructed and schematically shown in Fig. 2.

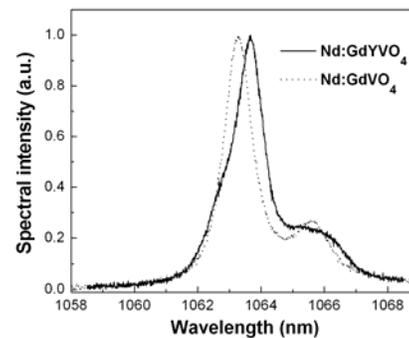


Fig. 1. Fluorescence spectra of the Nd:Gd_{0.64}Y_{0.36}VO₄ and Nd:GdVO₄ single crystals.

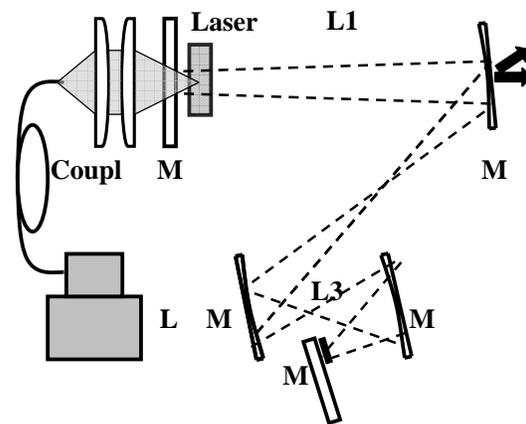


Fig. 2. Schematic of the mode-locked laser setup.

A fiber pigtailed laser diode bar with central wavelength of 808 nm at 20 °C was used as the pump source. The maximum pump power is 13 W. The pump light was focused into the laser medium by two coupling lenses with 1 cm focal length. The minimum beam waist of the focused pump light in the laser medium was about 200 μ m. A 5-mirror laser cavity was adopted to achieve a tightly focused laser beam at the saturable absorber and simultaneously an optimum mode matching in the laser crystal. The flat input mirror (M1) is high-reflection (HR) coated at 1064 nm and anti-reflection (AR) coated at 808 nm. The radii of curvature (ROC) of M2 and M3 are both 1000 mm while that of M4 is 300 mm. M3 and M4 are HR coated at 1064 nm. The mirror M2 acts as an output coupler, which has a transmission of 1%. During the experiments, the tilting angles of M2, M3, and M4 were kept as small as possible to minimize the cavity astigmatism. The SESAM (M5) was grown on *n*-GaAs (100) substrates by means of solid-source molecular beam epitaxy (SSMBE) with a 15% reflectivity modulation. It consisted of a 25-pair $\lambda/4n$ GaAs / AlAs DBR, five Ga_{0.69}In_{0.31}As/GaAsP quantum wells (QWs) sandwiched between GaAsP/GaAs spacers. The DBR had an over 100-nm high-reflectivity (> 99%) stopband centered at around 1060 nm. The band edge of the QWs was around 1070 nm.

The QWs were centered at/near the anti-node of the cosine type $I-\lambda$ cavity field. In order to make the SESAM fast, $1 \times 10^{12}/\text{cm}^2$ dose of proton was irradiated onto the SESAM sample. The lengths of arm L1 to L4 were 100 cm, 90 cm, 64 cm, and 20 cm respectively. The cavity was optimized for 10-W pump power level. At this pump power level, it gives a mode size of 210 μm in radius at the mirror M1, which matches the pump beam size, and a mode size of 70 μm in radius at the SESAM (M5) that provides high laser intensity in the saturable absorber.

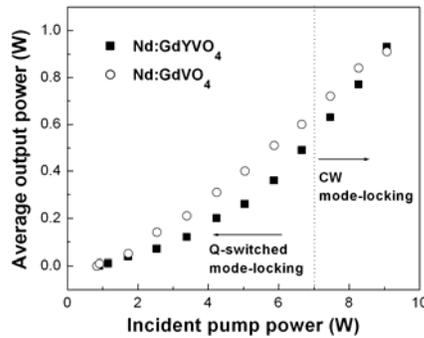


Fig. 3. Average output power versus input power of the mode-locked lasers.

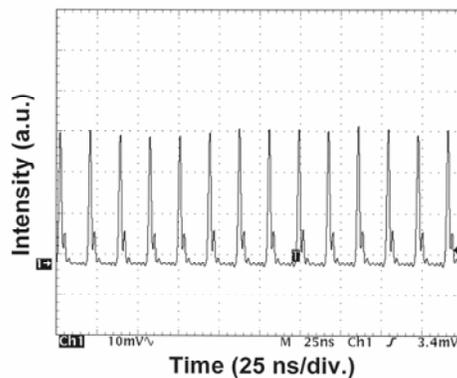


Fig. 4. Oscilloscope trace of the CW mode-locked Nd:Gd_{0.64}Y_{0.36}VO₄ laser pulse train.

With an appropriate alignment of the laser cavity, stable laser emission has been obtained. The two beam laser output from M2 was measured with a power meter. The average output power versus the incident pump power of the laser is shown in Fig. 3. Under the maximum incident pump power of 9 W, an maximum average output power of 0.93 W was obtained in the Nd:Gd_{0.64}Y_{0.36}VO₄ laser. The laser beam had a TEM₀₀ transverse mode and was almost linearly polarized with a polarization rate of 200:1. The laser began oscillation at the pump power of 0.9 W, while the stable CW mode-locking operation was only obtained when the pump power is above 7 W. It is to note that the CW mode-locking was obtained under a relative high pump power as 7 W. By using a similar mode-locked Nd:Gd_{0.64}Y_{0.36}VO₄ laser, the relation between the saturable absorption and the input energy fluence was investigated. It was found that the saturation

fluence of the semiconductor mirror is around 60 $\mu\text{J}/\text{cm}^2$, which is similar with the commercial SESAM. However, the modulation depth of the intensity-dependent transmission of the semiconductor saturable absorber is as high as 15%, which is believed to be responsible for a high CW mode-locking threshold. It is also worth to mention that the slope efficiency of the laser has lower value when the pump power is below 6W and obviously increased when the pump power is beyond 6 W. It is because the laser cavity is intended to optimize for the laser operation at the pump power in the region of 10 to 13 W. However, in practice, the SESAM was damaged when the pump power was higher than 9 W. Therefore, even higher output power could not be obtained for the current cavity design. Since the thermal focal length of the Nd:GdVO₄ crystal is quite different to that of the Nd:Gd_{0.64}Y_{0.36}VO₄, and the cavity is optimized according to the thermal properties of the Nd:Gd_{0.64}Y_{0.36}VO₄ single crystal, the slope efficiency change of the Nd:GdVO₄ laser was no obvious during the experimental pump power change range. Comparing with the Nd:Gd_{0.64}Y_{0.36}VO₄ laser, the Nd:GdVO₄ laser had a lower pumping threshold of 0.8 W, as a results of its larger emission cross-section than that of the Nd:Gd_{0.64}Y_{0.36}VO₄ crystal. The CW mode-locking threshold of the Nd:GdVO₄ laser was measured to be 6.6 W, which is also slightly lower than that of the Nd:Gd_{0.64}Y_{0.36}VO₄ laser.

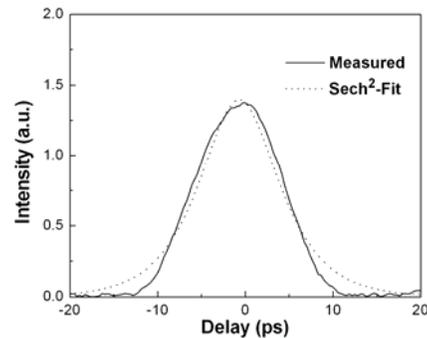


Fig. 5. Autocorrelation trace of the CW mode-locked Nd:Gd_{0.64}Y_{0.36}VO₄ laser pulses.

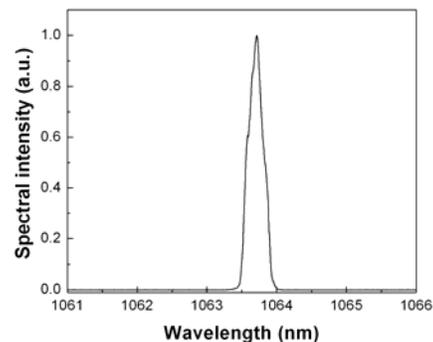


Fig. 6. Laser spectrum of the CW mode-locked Nd:Gd_{0.64}Y_{0.36}VO₄ laser pulses.

A typical time evolution of the mode-locked pulse train of the Nd:Gd_{0.64}Y_{0.36}VO₄ laser, measured by use of a fast photo detector and an oscilloscope (HEWLETT 54720D), is shown in Fig. 4. The time interval between two adjacent pulses is about 18 ns, which corresponds to the repetition rate of 55.6 MHz as determined by the cavity length. By use of a commercial noncollinear autocorrelator (FR-103XL), the autocorrelation trace of the mode-locked pulses was recorded as shown in Fig. 5. The FWHM width of the autocorrelation trace is about 11 ps. Under the assumption of a Sech² pulse profile, the pulse duration is calculated to be about 7.1 ps. Consequently, the peak power of the mode-locked laser was estimated to be about 2.4 kW. Figure 6 shows the emission spectrum of the laser measured with an optical spectrum analyzer (ANDO 6315B). The laser oscillated around 1063.7 nm and the spectral bandwidth of the mode-locked pulse was about 0.28 nm. The time-bandwidth product of the mode locked pulses is thus calculated to be 0.527.

A similar time evolution of the mode-locked pulses as shown in Fig. 4 has also been obtained from the mode-locked Nd:GdVO₄ laser. The corresponding autocorrelation trace and emission spectrum were measured and shown in Fig. 7 and Fig. 8, respectively. The FWHM width of the autocorrelation trace for the Nd:GdVO₄ laser is around 14 ps, under the assumption of Sech²-pulse profile, the pulse duration is estimated to be about 9 ps, which is slightly larger than that of the Nd:Gd_{0.64}Y_{0.36}VO₄ laser. Figure 8 shows that the mode-locked spectrum of the Nd:GdVO₄ laser has a bandwidth of 0.22 nm centered at 1063.3 nm. The time-bandwidth product of the mode-locked pulses is estimated to be 0.524. Based on our experiments it is to see that both of the laser crystals can be easily mode-locked with the SESAM. Nevertheless, with the Nd:Gd_{0.64}Y_{0.36}VO₄ mixed crystal CW mode-locked pulses of narrower pulse width and higher peak power can be obtained.

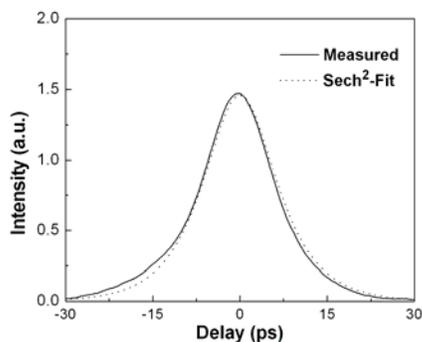


Fig. 7. Autocorrelation trace of the CW mode-locked Nd:GdVO₄ laser pulses.

It is to note that both of the laser crystals used in the experiments are a-cut. For the laser crystals cut along c direction, different laser performance is expected because of a different emission cross-sections and thermal conductivity [19]. Generally, since the c-cut Nd:Gd_xYV_{1-x}O₄ single crystal has a smaller emission cross-section than

that of the a-cut Nd:Gd_xYV_{1-x}O₄, it is believed that the c-cut Nd:Gd_xYV_{1-x}O₄ laser crystal is more suitable for Q-switching or Q-switched mode-locking. Nevertheless, the detailed comparison in the laser performance of the Nd:Gd_xYV_{1-x}O₄ with different cutting direction still needs to be investigated.

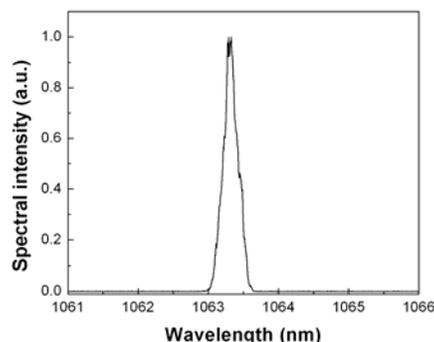


Fig. 8. Laser spectrum of the CW mode-locked Nd:GdVO₄ laser pulses

3. Conclusion

In conclusion, we have demonstrated continuous-wave mode locking in a diode-pumped Nd:Gd_{0.64}Y_{0.36}VO₄ laser with a semiconductor saturable absorber mirror. The mode-locked pulses are as short as 7.1 ps and have a peak power of 2.4 kW and a repetition rate of 55.6 MHz. Comparative studies between the mode-locking of the Nd:Gd_{0.64}Y_{0.36}VO₄ laser and the Nd:GdVO₄ laser were also carried out. Our results demonstrated that both crystals are suitable for the generation of picosecond-order optical pulses, however, the Nd:Gd_{0.64}Y_{0.36}VO₄ laser can achieve slightly narrower pulses than the Nd:GdVO₄ crystal laser does.

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