Comparative study of the mode-locking of $Nd:GdVO_4$ and Nd:YAG lasers with semiconductor saturable absorber mirrors

Bingyuan Zhang (张丙元)[1,2], Gang Li (李 港)[1], Meng Chen (陈 檬)[1], Yonggang Wang (王勇刚)[3], and Zhigang Zhang (张志刚)[1]

[1] *College of Laser Engineering, Beijing University of Technology, Beijing 100022*
[2] *College of Physics Science and Information Engineering , Liaocheng University, Shandong 252059*
[3] *Institute of Semiconductors, Chinese Academy of Science, Beijing 100081*

Received April 11, 2003

Stable continuous-wave passive mode-locking of diode-end-pumped $Nd:GdVO_4$ and Nd:YAG lasers with semiconductor saturable absorber mirrors (SESAMs) are reported. The comparative study shows that the $Nd:GdVO_4$ crystal is efficient to decrease the Q-switched mode-locking tendency, and easier to continuous-wave (CW) mode lock than Nd:YAG.

OCIS codes: 140.4050, 140.3580, 140.3540, 140.3530.

All solid-state passively mode-locked lasers operating in the infrared spectral regions have wide applications in the fields of industry, defence, medical treatment, and scientific research. For a picosecond system, neodymium (Nd) doped glasses and crystals such as YAG, YVO_4 and YLF have been extensively studied[1−4]. $Nd:GdVO_4$ crystal was firstly developed by Zagumennyi *et al.* in 1992[5], which possesses a few of desirable advantages over Nd:YAG. The stimulated-emission cross section of the $Nd:GdVO_4$ (7.6×10^{-19} cm^2)[6] is larger than that of Nd:YAG (2.8×10^{-19} cm^2)[1] at 1.06 μm. Also the absorption coefficient of $Nd:GdVO_4$ is even higher than that of Nd:YAG[1,6]. Another attractive property of the $Nd:GdVO_4$ is its short upper-state lifetime(90 μs)[5]. So far the few papers reporting on the $Nd:GdVO_4$ crystal are mainly concerned with its crystal growth, spectral characteristic, passively Q-switching, 1.06 μm and 1.34 μm laser action[6−10]. And few paper reported its performance of mode-locking with a semiconductor saturable absorber mirror (SESAM).

In this paper, we report the passive mode-locking of $Nd:GdVO_4$ and Nd:YAG with SESAMs. A comparison with Nd:YAG crystal under the same cavity configuration and pumping conditions is presented, which shows that $Nd:GdVO_4$ is more efficient than Nd:YAG for CW mode-locking.

The experimental configuration is shown in Fig. 1. This set-up has no astigmatism and is easy to ensure pure fundamental mode operation. The pump radiation was provided by a fiber-coupled laser diode (LD) operating at a wavelength near 808 nm.The output fiber had a diameter of 400 μm and a numerical aperture (NA) of 0.22. The pump beam from the fiber bundle end was focused into the laser crystal with a spot diameter of about 160 μm. The $Nd:GdVO_4$ (dimensions are of $3 \times 3 \times 5$ mm^3) and Nd:YAG ($\phi 3 \times 5$ mm^2) laser crystals used in our experiments had different Nd^{3+} concentration of 0.8 at.-% and 1 at.-%, respectively. The pump surfaces of $Nd:GdVO_4$ and Nd:YAG crystals were dielectrically coated to give a high reflectivity at 1064 nm laser wavelength and a high transmission at 808 nm pump wavelength. The other faces of the crystals were coated with a high transmission film at 1064 nm. L_3 and L_4 in Fig. 1 were both coated anti-reflection film at 1064 nm. L_3 was a convex lens and the focal length was 100 mm, which was used to compensate the thermal lensing effect in the crystal. We changed the focal length of the convex lens L_4 and the distance between L_4 and SESAM to adjust the laser spot on the SESAM. We placed an output coupler M in the cavity and adjusted the angle to change the output coefficient, at the angle of about 10°, the best output of 7% transmission at the oscillating wavelength was obtained.

When experiments were carried out under the same conditions for $Nd:GdVO_4$ and Nd:YAG, we obtained

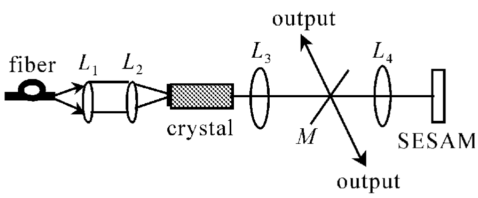

Fig. 1. Schematic of the diode-end-pumped passively mode-locked $Nd:GdVO_4$ and Nd:YAG lasers.

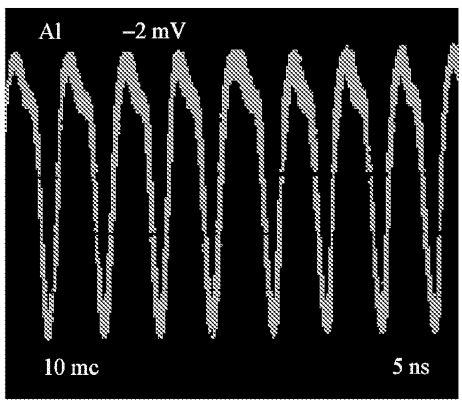

Fig. 2. Oscilloscope trace of CW mode-locked pulses.

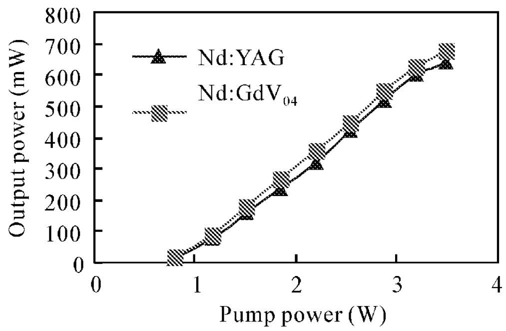

Fig. 3. Output powers of CW mode-locked Nd:GdVO$_4$ and Nd:YAG lasers as a function of pump power.

CW mode-locking (Fig. 2). Figure 3 displays the output power versus input power of the Nd:GdVO$_4$ and Nd:YAG lasers. The optical conversion efficiency is 20% for Nd:GdVO$_4$ and 18% for Nd:YAG, respectively, which is ascribed to the larger stimulated-emission cross section of the Nd:GdVO$_4$ than that of Nd:YAG. With the same pump power of 3.5 W, the output powers of 670 mW for Nd:GdVO$_4$ and 630 mW for Nd:YAG were obtained, respectively. In the experiment, the SESAM consists of a single 12 nm In$_{0.25}$Ga$_{0.75}$As quantum well on an AlGaAs Bragg mirror structure. The pulse duration measured with an autocorrelator is narrower than 10 ps.

When we employed several SESAMs with different properties, different results of the mode-locking of Nd:GdVO$_4$ and Nd:YAG were obtained. These SESAMs were grown by metal-organic chemical vapor deposition (MOCVD). The properties of them: #1 consists of a single 12 nm In$_{0.25}$Ga$_{0.75}$As quantum well on an AlGaAs Bragg mirror structure and its reflect coefficient is 96%, the growth temperature of which is 500°C; #2 consists of two quantum wells as #1 and its reflect coefficient is 92%, the growth temperature of which is 500°C; #3 consists of one quantum well as #1 and its reflect coefficient is 92%, the growth temperature of which is 400°C; #4 consists of one quantum well as #1 and has been handled specially, the growth temperature of which is 700°C. The results are shown in Table 1. For Nd:GdVO$_4$ we obtained stable CW mode-locking with four different SESAMs, but for Nd:YAG only the #1 SESAM is efficient for CW mode-locking (Fig. 2) and with other SESAMs we only obtained Q-switched mode-locking (QML) (Fig. 4).

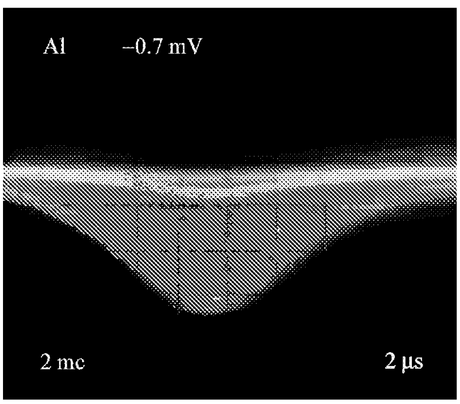

Fig. 4. Oscilloscope trace of Q-switched mode-locked pulses.

Table 1. The Mode-Locking Results of the Two Crystals with Different SESAMs

SESAM	Nd:GdVO$_4$	Nd:YAG
#1	CW	CW
#2	CW	QML
#3	CW	QML
#4	CW	QML

Table 2. The Pump Threshold of CW Mode-Locking of the Two Crystals with Different Lenses (Unit: W)

F (mm)	22	60	100
Nd:YAG	1.49	1	0.83
Nd:GdVO$_4$	1.24	0.9	0.78

Table 1 shows that the Nd:GdVO$_4$ crystal is efficient to decrease the Q-switched mode-locking tendency and is easier to CW mode lock than Nd:YAG, which is ascribed to the shorter upper-state lifetime and the higher emission cross section of Nd:GdVO$_4$[7,11,12].

When experiments were performed with different convex lens L_4 of 22 mm, 60 mm, 100 mm focal length F and #1 SESAM without other conditions changed in Fig. 1. Though CW mode-locking can be obtained for both Nd:GdVO$_4$ and Nd:YAG, the pump threshold (P_{th}) of CW mode-locking is different. The results were shown in Table 2. It shows that P_{th} is reduced with the focal length of L_4 increased. About the mechanism of that, we will make a thorough description in other article. More importantly, it shows that P_{th} of CW mode locking of Nd:GdVO$_4$ is lower than that of Nd:YAG, which is ascribed to the higher absorption coefficient and the bigger emission cross section of Nd:GdVO$_4$ than that of Nd:YAG.

In conclusion, we have achieved CW mode-locking of diode-end-pumped Nd:GdVO$_4$ and Nd:YAG lasers with SESAM, and the pulses duration obtained were both narrower than 10 ps. Through the comparative study of the mode-locking of the two crystals, we conclude that the Nd:GdVO$_4$ crystal is efficient to decrease the Q-switched mode-locking tendency, and easier to CW mode lock than Nd:YAG. The Nd:GdVO$_4$ crystal will be one of best laser crystals for diode-pumped CW mode-locked laser system.

This work was supported by the National Natural Science Foundation of China under Grant No. 3021001. B. Zhang's e-mail address is zhangbingyuan@sina.com.cn.

References

1. G. Mcconnell, A. I. Ferguson, and N. Langford, Appl. Phys. B **74,** 7 (2002).
2. G. J. Spuhler, R. Paschotta, and U. Keller, Opt. Lett. **24,** 528 (1999).
3. Y. F. Chen, S. W. Tsai, Y. P. Lan, and C. Wang, Opt. Lett. **26,** 199 (2001).
4. U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, and M. T. Asom, Opt. Lett. **17,** 505 (1992).

5. A. I. Zagumennyi, V. G. Ostroumov, I. A. Shcherbakov, T. Jensen, J. P. Meyn, and G. Huber, Sov. J. Quantum Electron. **22,** 1071 (1992).
6. C. Q. Wang, Y. T. Chow, L. Reekie, W. A. Gambling, H. J. Zhang, L. Zhu, and X. L. Meng, Appl. Phys. B **70,** 769 (2000).
7. T. Graf, A. I. Ferguson, E. Bente, D. Burns, and M. D. Dawson, Opt. Commun. **159,** 84 (1999).
8. J. H. Liu, Z. S. Shao, H. J. Zhang, X. L. Meng, L. Zhu, and M. H. Jiang, Optics & Laser Technology **31,** 459 (1999).
9. C. P. Wyss, W. Luthy, H. P. Weber, V. I. Vlsaov, Y. D. Zavartsev, P. A. Studennikin, A. I. Zagumennyi, and I. A. Shcherbakov, Appl. Phys. B **68,** 659 (1999).
10. C. L. Du, J. H. Liu, Z. P. Wang, G. B. Xu, X. G. Xu, K. Fu, X. L. Meng, and Z. S. Shao, Optics & Laser Technology **34,** 699 (2002).
11. A. Major, N. Langford, T. Graf, D. Burns, and A. I. Ferguson, Opt. Lett. **27,** 15 (2002).
12. C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, J. Opt. Soc. Am. B **16,** 46 (1999).