

Passive mode locking of diode-end-pumped Nd:GdVO₄ laser with an In_{0.25}Ga_{0.75}As output coupler

Bingyuan Zhang ^{a,b,*}, Gang Li ^c, Meng Chen ^c, Haijuan Yu ^c,
Yonggang Wang ^d, Xiaoyu Ma ^d

^a College of Laser Engineering, Beijing University of Technology, Beijing 100022, China

^b College of Physics Science and Information Engineering, Liaocheng University, Liaocheng 252059, China

^c College of Laser Engineering, Beijing University of Technology, Beijing 100022, China

^d Institute of Semiconductors, Chinese Academy of Science, Beijing 100081, China

Received 12 April 2004; received in revised form 23 July 2004; accepted 8 September 2004

Abstract

Passive mode locking of a diode-pumped Nd:GdVO₄ laser was demonstrated using In_{0.25}Ga_{0.75}As as saturable absorber as well as output coupler. The pulse width was measured to be about 16 ps with a repetition rate of 146 MHz. The average output power was 120 mW with pump power of 6 W. To our knowledge, this is the first demonstration on a passively mode-locked Nd:GdVO₄ laser by using an In_{0.25}Ga_{0.75}As output coupler.

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PACS: 42.55.X; 42.60.F

Keywords: Diode-end-pumped; Mode locking; Nd:GdVO₄; In_{0.25}Ga_{0.75}As

Nd:GdVO₄ is a relatively new laser crystal with many advantages such as the large stimulated emission cross-section and high-absorption coefficient at 808 nm. Table 1 show us the properties of Nd:YVO₄; Nd:YAG and Nd:GdVO₄ [1–3]. From Table 1 one can see that Nd:GdVO₄ has high-thermal conductivity, which is almost two

times higher than that of Nd:YVO₄. And its short upper-state lifetime combined with large stimulated emission cross-section is favorable to continuous-wave (CW) mode locking [4–6]. Therefore Nd:GdVO₄ is an attractive laser medium for mode locking.

Semiconductor saturable absorber devices like SESAMs have been established as a useful device for passive mode locking [1–6]. The main reason for this device's utility is that both the linear and nonlinear optical properties can be engineered over

* Corresponding author. Tel.: +86 10 67391478; fax: +86 10 67396553.

E-mail address: zhangbingyuan@sina.com.cn (B. Zhang).

Table 1
Properties of Nd:YVO₄, Nd:YAG and Nd:GdVO₄

Parameter	Nd:YVO ₄ (1.1 at.%)	Nd:YAG (1 at.%)	Nd:GdVO ₄ (0.8 at.%)
Transition wavelength (nm)	1064	1064	1064
Refractive index (at 1064 nm)	$n_0 = 1.96$ $n_e = 2.166$	1.82	$n_0 = 1.972$ $n_e = 2.192$
Thermal conductivity (Wm ⁻¹ K ⁻¹)	5.1	11.1	11.7
Emission cross-section (10 ⁻¹⁹ cm ²)	25	2.8	7.6
Absorption coefficient (at 808 nm cm ⁻¹)	36	11	74
Lifetime (μs)	95	230	90
Pulse duration (ps)	2.8	6.8	8

a wide range, allowing for freedom in the specific laser cavity design. Generally the SESAM is mostly used as an end mirror of a standing-wave cavity, which can lead to a higher complexity of the laser setup. This was observed for example especially in passively mode locked microchip laser [7,8]. So there is need for a device which combines the nonlinear properties of the SESAM with an output coupler [9], and which can make the laser more compact and reliable and useful. Some papers employed GaAs as saturable absorber as well as output coupler for passive mode locking and Q-switching [10,11]. In this paper, we employed an In_{0.25}Ga_{0.75}As wafer that combines the nonlinear properties of the SESAM with an output coupler. The In_{0.25}Ga_{0.75}As wafer was grown by metal-organic chemical vapor deposition (MOCVD) at low temperature. Adjusting the growth temperature can control absorber recovery time of In_{0.25}Ga_{0.75}As, and the modulation depth depends on the thickness of the absorption layer. The structure of In_{0.25}Ga_{0.75}As is as simple as that of GaAs, however, it does not work in the principle of two-photon absorption (TPA) that leads to a nonlinear change of refractive index. When the ratio of In to Ga is changed, the In_{0.25}Ga_{0.75}As wafer can be used to mode locking of lasers at different wavelength, while GaAs is only for the wavelength near 1060 nm. So the In_{0.25}Ga_{0.75}As wafer has great potential for passive mode locking and Q-switching as saturable absorber as well as output coupler.

In this paper, we report on a simple experimental realization of CW mode locking in a Nd:GdVO₄ laser. By using In_{0.25}Ga_{0.75}As as the saturable absorber as well as the output coupler, we have achieved the continuous-wave mode lock-

ing with pulse duration as short as 16 ps. To our knowledge, this is the first demonstration of passively mode locked Nd:GdVO₄ laser with an In_{0.25}Ga_{0.75}As output coupler.

The schematic of the experimental setup is shown in Fig. 1. This set-up has no astigmatism. The pump source was provided by a fiber-coupled laser diode (LD) with central wavelength of 808 nm. The pump beam from the fiber end was focused into the laser crystal with a spot diameter of about 160 μm. The Nd:GdVO₄ laser crystals used in our experiments has a Nd³⁺-doping concentration of 1 at.% and a dimension of 3 mm × 3 mm in cross-section and 5 mm in length. The pump surface of Nd:GdVO₄ crystal was dielectrically coated to give a high reflectivity at 1064 nm laser wavelength and a high transmission at 808 nm pump wavelength. The other face of the crystal was coated with a high transmission film at 1064 nm. To efficiently remove the generated heat, the crystal was wrapped with indium foil and tightly mounted in a water-cooled copper holder, and the water temperature was maintained at 20 °C. L₃ was a convex lens with the focal length of 100 mm, which was used to compensate the thermal lensing effect in the crystal. L₃ and L₄ was separated by about 90 cm. L₄ also was a convex lens, which was used to focus the laser on In_{0.25}

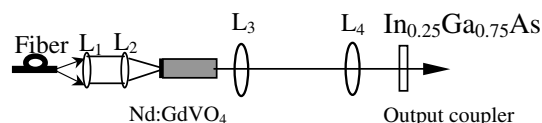


Fig. 1. Schematic of the diode-end-pumped passively mode-locked Nd:GdVO₄ laser with In_{0.25}Ga_{0.75}As.

Ga_{0.75}As. One side of the absorber (toward the cavity) was coated with anti-reflection coating at 1.06 μm , which was a 1/4 wavelength thickness of the hybrid of ZrO₂ and Y₂O₃ (4:1), and the other side of the absorber was deposited with high reflection film composed of Al₂O₃/Si/SiO₂/Si multiple layers to obtain high reflectivity. In order to make it as an output coupler we make the transmission rate of the absorber near 10%. The heat load on the In_{0.25}Ga_{0.75}As was handled simply by mounting the In_{0.25}Ga_{0.75}As on a small copper heat sink with a hole.

In the experiment, we change the focal length of L₄ and the distance between L₄ and In_{0.25}Ga_{0.75}As to adjust the laser spot on the In_{0.25}Ga_{0.75}As. We employed three different focusing lens ($F = 22, 60, 100$ mm), but only with the 22-mm focusing lens we obtained the CW mode locking. We attribute this to that the focusing lens of 60 and 100 mm could not provide enough power density in the saturable absorber for CW mode locking. With ABCD computation we got a beam radius of 45 μm in the laser crystal and a beam radius of 10 μm in the saturable absorber with the 22-mm focusing lens that can provide high laser intensity for the saturable absorber with a saturation fluence of 100 $\mu\text{J}/\text{cm}^2$.

With the cavity shown in Fig. 1, the laser average output power as a function of the available incident pump power was investigated, and the result was depicted in Fig. 2. With the change of

pump power, laser outputs follow a general behavior of three states (CW oscillation, Q-switched mode-locking, CW mode locking). When the pump power is near oscillation threshold of 2.2 W, the output is effectively CW oscillation. Slightly increasing the pump power initiate a Q-switched mode-locking. Fig. 3 shows the oscilloscope trace of Q-switched mode locking envelopes at a Q-switched repetition of 58.8 kHz. The Q-switched mode locking envelope with a half width of 5 μs consist of many mode locked pulses with repetition of about 146-MHz (not depicted in Fig. 3). When the pump power is increased to 3.4 W, we obtained stable CW mode locking. The oscilloscope trace of mode locked pulses is shown in Fig. 4. The time between two pulses is 6.84 ns and the repetition rate is 146-MHz. The pulse duration of 16 ps was measured with a nonlinear second-harmonic-generation autocorrelator and the autocorrelation trace was shown in Fig. 5. The average output power of the mode locked laser was 120 mW with 6 W pump power. To make a comparison we measured the CW output of the laser with a $T_{\text{out}} = 10\%$ flat mirror instead of the saturable absorber. At the pump power of 6 W, the output power of 400 mW was obtained. Both the CW and mode-locked output power had high threshold and low slope efficiency. We attribute this to two factors, one of which is the poor practical mode matching between the pump beam and the laser

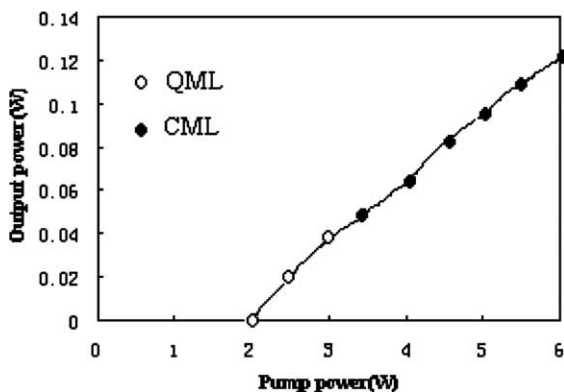


Fig. 2. Dependence of the average output power versus the pump power. CW mode locking was obtained at the 3.4 W pump power.

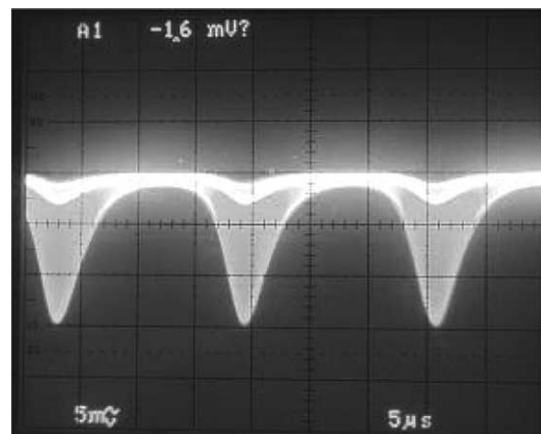


Fig. 3. Pulse train of the Q-switched mode-locked Nd:GdVO₄ laser with In_{0.25}Ga_{0.75}As.

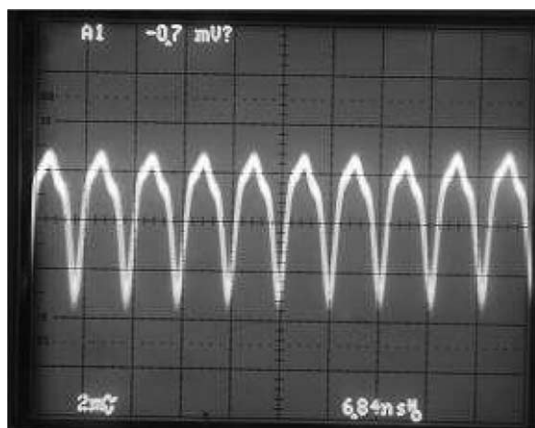


Fig. 4. Pulse train of the CW mode-locked Nd:GdVO₄ laser with In_{0.25}Ga_{0.75}As.

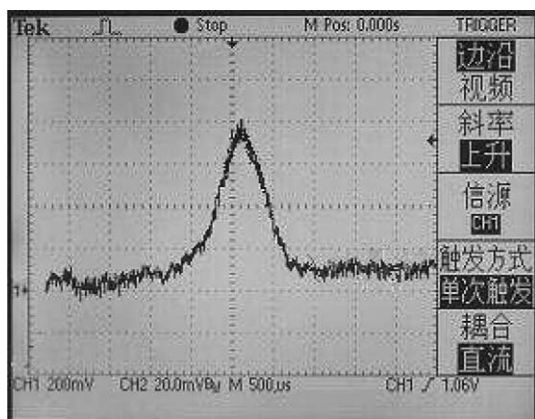


Fig. 5. Autocorrelation of CW mode-locked Nd:GdVO₄ laser with In_{0.25}Ga_{0.75}As.

beam achieved in the laser. Although the cavity parameters had been selected to possibly achieve an optimum mode matching between the pump beam size change along the laser crystal, the pump beam size variation practically limited the total mode-matching efficiency regardless of the laser beam size. The other factor is the linear losses of saturable absorber, which are contributed mainly to the residual losses in the undoped GaAs substrate and the imperfect AR coating.

In the experiment, to investigate the homogeneity of the present absorber we swept the beam spot

on a different region of the saturable absorber. It was found that the mode-locking operation is insensitive to the position of the saturable absorber. The stability of the laser was investigated by using an oscilloscope. When the pump power was higher than the threshold of CW mode-locking, the laser kept stable pure CW mode-locking without Q-switching instability. In the experiment we observed no change in the spatial shape when the mode-locking started and the laser has good TEM₀₀ mode.

In conclusion, a diode-end-pumped passively mode-locked Nd:GdVO₄ laser with an In_{0.25}Ga_{0.75} output coupler was realized. Stable CW mode-locking was achieved with 16 ps pulse duration at a repetition rate of 146 MHz, and 120 mW output powers at pump power of 6 W. Although the slope efficiency is low at present, the experimental results indicate that In_{0.25}Ga_{0.75}As is a promising element for short pulse generation and potentially useful for miniaturization and simplification of solid-state mode-locked lasers.

References

- [1] U. Keller, Appl. Phys. B 58 (1994) 347.
- [2] C.Q. Wang, Y.T. Chow, L. Reekie, W.A. Gambling, H.J. Zhang, L. Zhu, X.L. Meng, Appl. Phys. B 70 (2000) 769.
- [3] U. Keller, D.A.B. Miller, G.D. Boyd, T.H. Chiu, J.F. Ferguson, M.T. Asom, Opt. Lett. 17 (1992) 505.
- [4] U. Keller, K.J. Weingarten, F.X. Kartner, D. Kopf, B. Braun, I.D. Jung, R. Fluck, C. Honninger, J. aus der Au, J. Sel. Top. Quantum Electron. (JSTQE) 2 (3) (1996) 435.
- [5] Bingyuan Zhang, Gang Li, Meng Chen, Yonggang Wang, Zhigang Zhang, Opt. Lett. 28 (19) (2003) 1829.
- [6] Bingyuan Zhang, Gang Li, Meng Chen, Yonggang Wang, Zhigang Zhang, Chin. Opt. Lett. 1 (8) (2003) 477.
- [7] B. Braun, F.X. Kärtner, M. Moser, G. Zhang, U. Keller, Opt. Lett. 22 (1997) 381.
- [8] G.J. Spühler, R. Paschotta, R. Fluck, B. Braun, M. Moser, G. Zhang, E. Gini, U. Keller, J. Opt. Soc. Am. B 16 (1999) 376.
- [9] G.J. Spühler, S. Reffert, M. Haiml, M. Moser, U. Keller, Appl. Phys. Lett. 78 (18) (2001) 30.
- [10] J. Kong, D.Y. Tang, J. Lu, Kueda, H. Yagi, T. Yanagitani, Opt. Commun. 237 (2004) 165.
- [11] Jianhui Gu, Feng Zhou, Kah Tau Wan, Tuan Kay Lim, Siu-Chung Tam, Yee Loy Lam, Desheng Xu, Zuhai Cheng, Opt. Lasers Eng. 35 (2001) 299.