Diode-pumped passively Q-switched Nd:LuVO$_4$ laser at 916 nm

Kunna He [a,b,*], Chunqing Gao [a], Zhiyi Wei [b], Dehua Li [b], Zhiguo Zhang [b], HuaiJin Zhang [c], Jiyang Wang [c]

[a] Department of Opto-Electronics, Beijing Institute of Technology, Beijing 100081, China
[b] Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, P.O. Box 603, Beijing 100190, China
[c] National Laboratory of Crystal Materials and Institute of Crystal Materials, Shandong University, Jinan 250100, China

ARTICLE INFO

ABSTRACT

We demonstrate a passively Q-switched Nd:LuVO$_4$ laser at 916 nm by using a Nd, Cr:YAG crystal as the saturable absorber. As we know, it is the first time to realize the laser with a simple linear resonator. When the incident pump power increased from 14.6 W to 23.7 W, the pulse width of the Q-switched laser decreased from 24 ns to 21 ns. The pulse width was insensitive to the incident pump power in the experiment. The average output power of 288 mW with repetition rate of 39 kHz was obtained at an incident pump power of 22.5 W, with the optical-to-optical efficiency and slope efficiency 1.3% and 3.6%, respectively.

1. Introduction

Nd:LuVO$_4$ is a kind of Nd doped vanadate crystal developed by Maunier et al. in 2002 [1]. Just like its well-known family members of Nd:YVO$_4$ and Nd:GdVO$_4$, Nd:LuVO$_4$ has many superior optical properties. First of all, it has large absorption cross-section around 809 nm and large emission cross-section around 1060 nm which are even larger than those of the Nd:YVO$_4$ and Nd:GdVO$_4$. Secondly, it has significant large absorption cross-section around 880 nm, which is helpful to the laser operation under direct pumping [2]. Thirdly, its naturally polarized emission can avoid the thermally induced birefringence affecting isotropic hosts like Nd:YAG. Last but not least, it may also be a good self-Raman laser material like Nd:YVO$_4$ [3] and Nd:GdVO$_4$ [4]. The Nd:LuVO$_4$'s main emission bands located at 916, 1066 and 1342 nm. The $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition at 916 nm is very difficult to obtain due to difficulties such as serious re-absorption loss and very small stimulated-emission cross-section compared with the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition at 1066 nm. The $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition system of Nd:LuVO$_4$ is a quasi-three-level system and has received much attention since intra-cavity frequency doubling Nd^{3+} lasers near 900 nm has been

recognized as an effective way to realize the deep blue laser which ensured extensive applications in many fields for their short wavelength and large photon energy. In 2006, our group realized the 916 nm Nd:LuVO$_4$ laser with linear resonator for the first time [5]. Since then we realized the 458 nm Nd:LuVO$_4$ laser with linear [6] and Z type [7] resonators, and the operation of A–O Q-switched [8] 916 nm Nd:LuVO$_4$ laser.

Q-switching of solid-state lasers is an effective technique to generate giant pulses. Passive Q-switching is generally simple, compact, highly efficient and economic compared with active Q-switching. As far as we know, there has no report on the passive Q-switching operation at 916 nm with Nd:LuVO$_4$ laser. In this paper, we will report the passively Q-switched Nd:LuVO$_4$ laser at 916 nm for the first time as we know.

Among many saturable absorbers that used for passively Q-switched lasers, Cr:YAG has become the most promising one due to its good optical and physical properties such as large absorption bands, high thermal conductivity and high damage threshold. Nd, Cr:YAG is also a popular saturable absorber used for Q-switching and mode-locking [9,10]. It acts as a fast saturable absorber for mode-locking with high intra-cavity intensity, but with relatively lower intra-cavity intensity it acts only as a slow saturable absorber for Q-switching. We use the Nd, Cr:YAG crystal as the saturable absorber for the reason that it has lower saturation intensity compared with Cr:YAG [11]. In our experiment, higher average output power with narrower pulse width than those of the A–O Q-switched 916 nm Nd:LuVO$_4$ laser [8] has been obtained.

---

* Corresponding author. Address: Department of Opto-Electronics, Beijing Institute of Technology, Beijing 100081, China. Tel./fax: +86 10 82649074.
E-mail address: hekunna@aphy.iphy.ac.cn (K. He).

2. Experimental setup

The experimental setup is shown in Fig. 1. The whole length of the resonator was 22 mm. The pump source was a high-brightness fiber-coupled CW laser diode (LD) with a center wavelength of 806 nm at 28 °C and spectrum width of 3.5 nm (FWHM). The diameter of the fiber core and the numerical aperture of the LD was 200 μm and 0.22, respectively. A 1:1 coupling system was used to inject the pump laser into the c-cut Nd:LuVO$_4$ crystal with a size of $3 \times 3 \times 5.5$ mm^3 and Nd^{3+} concentration of 0.2 at.%. The Nd, Cr:YAG saturable absorber with small signal transmission of 91% was cut at the dimensions of Φ 5 × 1 mm^3. The absorption spectrum of Nd, Cr:YAG crystal was illustrated in Fig. 2. To keep a stable and efficient output, The Nd:LuVO$_4$ crystal and the Nd, Cr:YAG saturable absorber were both wrapped with the indium foils and mounted in water-cooled copper blocks which were controlled at 6 °C. To reduce the cavity loss, the Nd:LuVO$_4$ and the Nd, Cr:YAG saturable absorber were all coated on two facets for HT at 809, 916, 1066 and 1342 nm. The mirror M1 with a radius curvature of 50 mm was coated for HR at 916 nm and HT at 809 nm. The output mirror M2 was a plane mirror with transmission of 3.5% at 916 nm. According to the second threshold condition [12] and resonator analysis with the ABCD matrix we placed the Nd, Cr:YAG as close as possible to the output mirror where the laser beam spot size was the minimum. The reason is the bigger the ratio of the effective laser beam area in the gain medium and in the saturable absorber, the easier the operation of Q-switching. The Q-switched laser signal was detected by a fast photodiode detector with a rising time of <1 ns and a 500 MHz Tektronix oscilloscope.

3. Experimental results and discussion

We measured the laser spectrum of the passively Q-switched laser and illustrated the result in Fig. 3, from which we can see that the peak emission wavelength was 916 nm and the full width at half maximum (FWHM) was smaller than 2 nm.
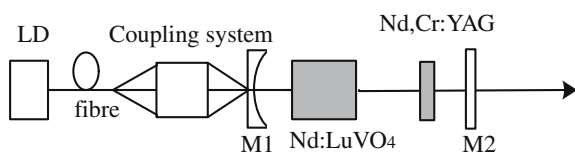

Fig. 1. Schematic of the diode-pumped passively Q-switched 916 nm Nd:LuVO$_4$ laser with Nd, Cr:YAG as the saturable absorber.
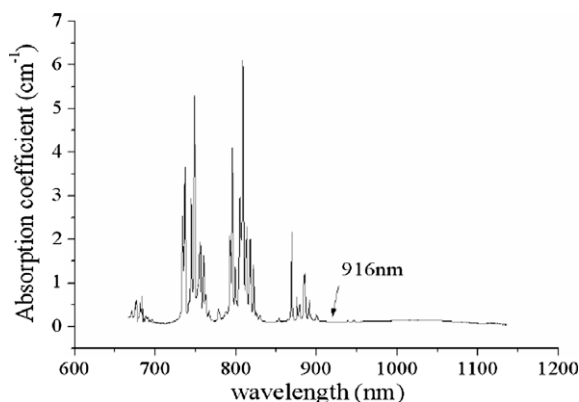

Fig. 2. Absorption spectrum of Nd, Cr:YAG crystal.

The average output power of the passively Q-switched laser versus the incident pump power under the optimum condition is shown in Fig. 4. It was shown that the threshold pump power was 14.8 W. With the increase of the incident pump power the average output power almost increased linearly until the incident pump power beyond 22.5 W where the output power began to drop due to the severe thermal lens effect. The maximum output power of 288 mW was obtained at an incident pump power of 22.5 W with an optical-to-optical conversion efficiency of 1.3% and a slope efficiency of 3.6%. The maximum output power was apparently higher than that in Ref. [8]. The high laser threshold in our experiment was possibly caused by several reasons listed below. Firstly, the 916 nm laser emission belongs to the quasi-three-level laser transition. The lower laser level is in the thermally populated ground state which will lead to a significant re-absorption loss at the room temperature. Secondly, compared with the four-level laser transition, the quasi-three-level laser transition usually has a smaller stimulated-emission cross-section. The stimulated-emission cross-section of Nd:LuVO$_4$ at the four-level of 1066 nm was about 146×10^{-20} cm^2, but its stimulated-emission cross-section at the quasi-three-level has not been reported as far as we know. Referencing to the stimulated-emission cross-section at the quasi-three-level of other Nd doped vanadate crystals like the Nd:YVO$_4$ (4.8×10^{-20} cm^2 (π); 4.3×10^{-20} cm^2 (σ)) and the Nd:GdVO$_4$ (6.6×10^{-20} cm^2 (π); 5.6×10^{-20} cm^2 (σ)), we can
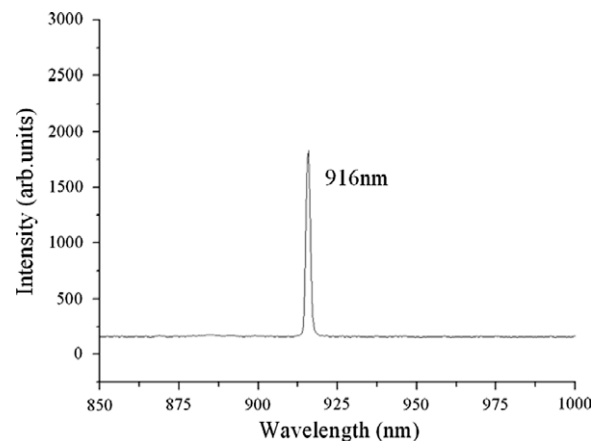

Fig. 3. Spectrum of the diode-pumped passively Q-switched Nd:LuVO$_4$ laser at 916 nm.
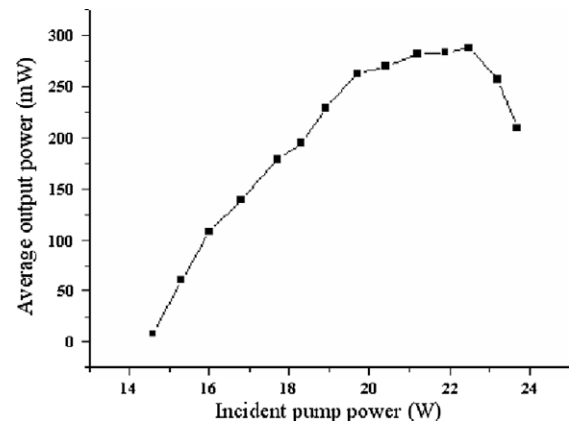

Fig. 4. Average output power of the 916 nm pulsed laser versus the incident pump power.

deduce that the small stimulated-emission cross-section at the quasi-three-level will result in the increase of the threshold of the quasi-three-level Q-switched laser. Thirdly, lower signal transmission causes larger loss in the cavity before the Q-switched laser emission. The small signal transmission of the Nd, Cr:YAG we used was lower compared with the optimum parameter of the quasi-three-level Q-switched laser in our experiment. Additionally, the central wavelength of the pump source departed about 2.5 nm from the central wavelength (809 nm) of the absorption bands of the Nd:LuVO$_4$ crystal. It was unfavorable for the utilization of the incident pump power. In our experiment the thermal lens focal length of the Nd:LuVO$_4$ crystal measured with plat–plat cavity method was less than 60 mm under the incident pump power of 22.5 W. Resonator analysis with the ABCD matrix illustrated that the spot radius of the pump light in the Nd:LuVO$_4$ crystal was about 110 µm. The far-field beam spatial profile of the 916 nm Q-switched laser at output power of 288 mW was measured by using a small pinhole scanning across the laser beam. The data and the Gaussian curve fitted result are shown in Fig. 5, from which we can see that the laser was oscillated in the quasi-fundamental transverse mode.

Figs. 6 and 7 shows the typical temporal shape of single Q-switched pulse with a pulse width of 24 ns and the pulse train with 20 kHz, respectively, at the incident pump power of 16 W. As shown in Fig. 7, the Q-switched pulse train was very stable with
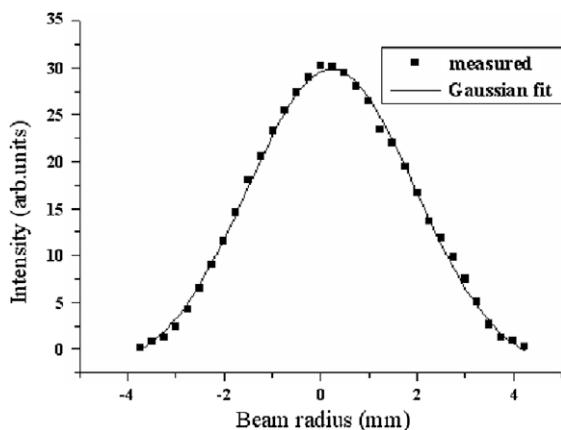

Fig. 7. Pulse train of passively Q-switched 916 nm Nd:LuVO$_4$ laser with 20 kHz under 16 W incident pump power.

Fig. 5. Far-field beam spatial profile of the output laser.
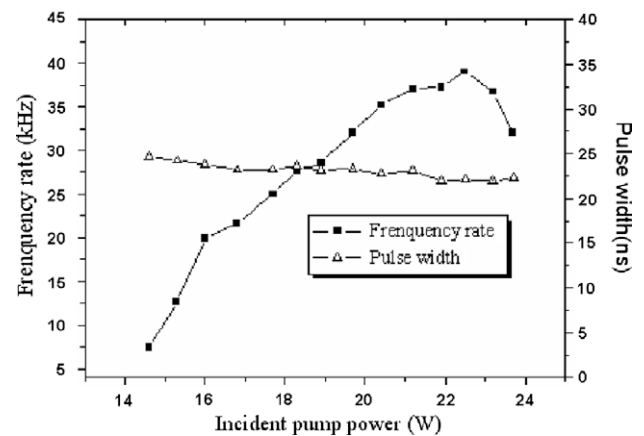
Fig. 8. Repetition rate and pulse width of the 916 nm pulsed laser versus the incident pump power.

a pulse amplitude and repetition rate jitter of less than 2%. The pulse amplitude and the repetition rate jitter increased with the incident pump power. The repetition rate and pulse width of the passively Q-switched laser with respect to the incident pump power is shown in Fig. 8. It is clear that at the beginning the repetition rate almost linearly increased and the repetition rate reached 39 kHz at an incident pump power of 22.5 W, but with further increasing the incident pump power the repetition rate began to decrease. The phenomenon was similar with those occurred in Refs. [13,14] and the reason is possibly the impact of the severe thermal lens effect. From Fig. 8 we also observed that the pulse width of the passively Q-switched laser was insensitive to the incident pump power. When the incident pump power increased from 14.6 W to 23.7 W the pulse width decreased from 24 ns to 21 ns, similar results were demonstrated experimentally by other groups [15,16] though our result was not consistent with those obtained in some reports [17,18]. The pulse width under different incident pump power was shorter than that of the A–O Q-switched 916 nm Nd:LuVO$_4$ laser [8].

4. Conclusions

We have demonstrated the stable passively Q-switched 916 nm Nd:LuVO$_4$ laser with Nd, Cr:YAG as a saturable absorber for the first time as we know. The pulse width of the passively Q-switched

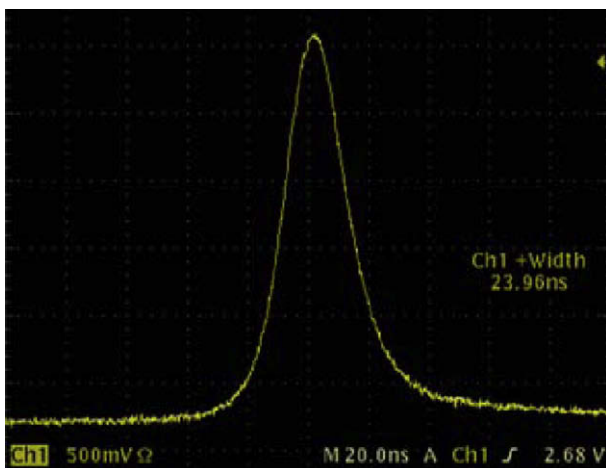**Fig. 6.** Single pulse of passively Q-switched 916 nm Nd:LuVO$_4$ laser with a pulse width of 24 ns under 16 W incident pump power.
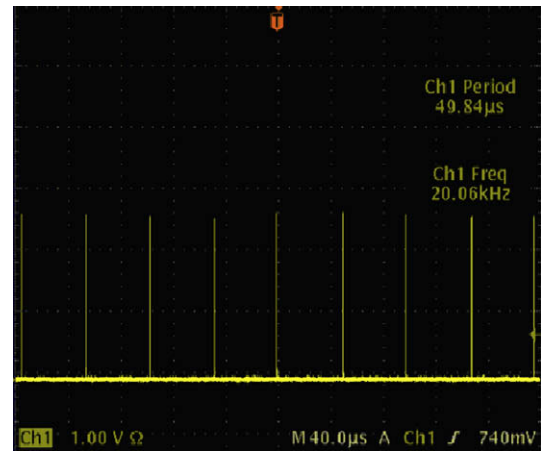
laser was insensitive to the incident pump power. When the incident pump power increased from 14.6 W to 23.7 W the pulse width decreased from 24 ns to 21 ns. At an incident pump power of 22.5 W, the average output power of 288 mW [15,16] with 39 kHz repetition rate was achieved, the corresponding optical–optical efficiency and slope efficiency was 1.3% and 3.6%, respectively. We expect to get better result with optimized experiment condition and we also expect that the 916 nm Q-switched Nd:LuVO$_4$ laser has wider applications in the future.

Acknowledgments

References

[1] C. Maunier, J.L. Doualan, R. Moncorgé, A. Speghini, M. Bettinelli, E. Cavalli, J. Opt. Soc. Am. B 19 (2002) 1794.
[2] R. Lavi, S. Jackel, Y. Tzuk, M. Winik, E. Lebiush, M. Katz, I. Paiss, Appl. Opt. 38 (1999) 7382.
[3] Baoshan Wang, Huiming Tan, Jiying Peng, Jieguang Miao, Lanlan Gao, Opt. Commun. 271 (2007) 555.
[4] Wang Baoshan, Tan Huiming, Peng Jiying, Miao Jieguang, Gao Lanlan, Opt. Mater. 29 (2007) 1817.
[5] Chunyu Zhang, Ling Zhang, Zhiyi Wei, Chi Zhang, Yongbing Long, Zhiguo Zhang, HuaiJin Zhang, Jiyang Wang, Opt. Lett. 31 (2006) 1435.
[6] Zhang Ling, Chun-Yu Zhang, Zhi-Yi Wei, Zhang Chi, Yong-Bing Long, Zhi-Guo Zhang, Huai-Jin Zhang, Ji-Yang Wang, Chin. Phys. Lett. 23 (2006) 1192.
[7] Kunna He, Chunqing Gao, Zhiyi Wei, Dehua Li, Zhiguo Zhang, HuaiJin Zhang, Jiyang Wang, Opt. Commun. 281 (2008) 3853.
[8] Chun-Yu Zhang, Chun-Qing Gao, Zhi-Feng Lin, Ming-Wei Gao, Zhang Ling, Zhi-Yi Wei, Zhang Chi, Zhi-Guo Zhang, Huai-Jin Zhang, Ji-Yang Wang, Chin. Phys. Lett. 23 (2006) 2763.
[9] Sumei Wang, Qinan Li, Shifeng Du, Qiulin Zhang, Yuxian Shi, Jie Xing, Dongxiang Zhang, Baohua Feng, Zhiguo Zhang, Shiwen Zhang, Opt. Commun. 277 (2007) 130.
[10] Jiang Li, Yusong Wu, Yubai Pan, Jingkun Guo, J. Non-Cryst. Solids 352 (2006) 2404.
[11] Lin Yang, B. Feng, Z. Zhang, V. Gaebler, B. Liu, H.J. Eichler, Opt. Mater. 22 (2003) 59.
[12] Y.F. Chen, Y.P. Lan, H.L. Chang, J. Quant. Electron. 37 (2001) 462.
[13] S.P. Ng, D.Y. Tang, L.J. Qin, X.L. Meng, Opt. Commun. 229 (2004) 331.
[14] Jieguang Miao, Baoshan Wang, Jiying Peng, Huiming Tan, Huikun Bian, Opt. Laser Technol. 40 (2008) 137.
[15] A. Agnesil, S. Dell'acqua, Appl. Phys. B 76 (2003) 351.
[16] M. Montes, C. de las Heras, D. Jaque, Opt. Mater. 28 (2006) 408.
[17] Karol Waichman, Leonid Kravchik, Jacob Kagan, Christophe Labbe, Yehoshua Kalisky, Opt. Mater. 16 (2001) 163.
[18] Zhang Ling, Li Chun-Yong, Feng Bao-Hua, Wei Zhi-Yi, Li De-Hua, Fu Pan-Ming, Zhang Zhi-Guo, Chin. Phys. Lett. 22 (2005) 1420.