

Continuous-wave and passively Q-switched Nd:GGG laser

Y. F. MA*, H. T. DANG, F. H. LIU

Shaanxi Engineering Research Center of Controllable Neutron Source, School of Science, Xijing University, Xi'an, 710123, China

A diode-pumped passively Q-switched 1066 nm laser with Nd:GGG crystal was demonstrated. The maximum output power was 4.5 W under the absorbed pump power of 12.56 W, with a slope efficiency of 40% in the continuous-wave (CW) operation. The characteristics of the passively Q-switched Nd:GGG laser with the Cr⁴⁺:YAG saturable absorbers were researched. When the Cr⁴⁺:YAG crystal with the initial transmission (T_0) of 85% at 1.06 μm was placed in the cavity, the maximum repetition rate and the minimum pulse width were 6.7 kHz and 28.7 ns, respectively.

(Received October 15, 2019; accepted April 9, 2020)

Keywords: Nd:GGG, Passively Q-switched, Cr⁴⁺:YAG, DPSSL

1. Introduction

With the continuous development of laser technology, lasers are increasingly used in military, industrial, scientific research and daily life [1-4]. Diode-pumped solid-state lasers (DPSSL) have become the research hotspot of laser devices due to their simple structure, high efficiency and good stability [5-7]. In recent years, solid heat capacity lasers are rapidly developed, and the Nd:GGG crystal is the material of choice for high-energy heat capacity lasers [8]. Compared with Nd:YAG laser, which has always played an important role in high-power heat capacity lasers, Nd:GGG laser has a series of advantages, such as fast growth rate, high doping concentration, no stress core, much higher mechanical strength and thermal conductivity [9]. In addition, it is believed that Nd:GGG can achieve rapid cooling of the crystal and have high laser efficiency, good absorption and energy storage performance of pump light [10,11]. Therefore, it was selected as the laser working substance of the 100 kW short-range strategic laser weapon by United States [12].

In recent years, in order to obtain a more compact end-pumped Q-switched laser, the passively Q-switched method has widely attracted attention of researchers [13-16]. Compared with the actively Q-switched technology, the passively Q-switched laser has the advantages of simple structure and no require for driving source [17-20]. Among commonly used passively Q-switched materials, Cr⁴⁺:YAG saturable absorption crystal has the advantages of good thermal conductivity, high damage threshold, stable optical properties and no degradation. Moreover, Cr⁴⁺:YAG crystal has a broad absorption bandwidth around 0.9-1.2 μm and excellent saturable absorption characteristics. So it is particularly

suitable for passively Q-switched lasers with Nd³⁺ doped laser materials [21-23].

In this paper, we demonstrated a passively Q-switched 1.06 μm Nd:GGG laser. The continuous-wave (CW) output characteristics with varies output couplers were investigated and the passively Q-switched laser performance of Nd:GGG crystal was studied using Cr⁴⁺:YAG crystal with initial transmission of 85% and 95%.

2. Experimental setup

Fig. 1 shows the diagram of passively Q-switched Nd:GGG laser experimental setup.

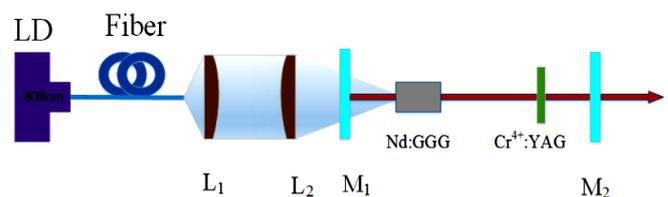


Fig. 1. Passively Q-switched Nd:GGG laser experimental device (color online)

A fiber-coupled 808 nm diode laser with the fiber diameter of 400 μm was used as the pumping source and the pump beam waist radius was 320 μm . The maximum output power of the diode laser was 50 W and the numerical aperture of the fiber was 0.22. L_1 and L_2 with the focal length of 26.7 mm and 42.7 mm respectively constituted collimation focusing system. The crystal size

was $3 \times 3 \times 8 \text{ mm}^3$, with a Nd^{3+} concentration of 3 at.%. The crystal with indium foil wrapped was set into a water-cooled copper block to reduce thermal effects. The water-cooling system can keep the crystal at $18 \text{ }^\circ\text{C}$. The flat mirror M_1 was highly transparent to the pump light of 808 nm wavelength and fully reflected the light of $1.06 \text{ }\mu\text{m}$. The output flat mirror M_2 was chosen with varies transmission of 2%, 5% and 10% respectively in the CW operation. The saturable absorbers taken in the experiment were $\text{Cr}^{4+}:\text{YAG}$ with initial transmission (T_0) of 85% and 95% at $1.06 \text{ }\mu\text{m}$. The length of laser cavity was kept at 40 mm.

3. Results and discussion

Firstly, CW operations were studied. The output power with varies output couplers were measured and showed in Fig. 2. From Fig. 2, we can see that CW output power increased as the pump power increased. With the output coupler's transmission of 5%, the maximum of CW output power was 4.5 W when the absorbed pump power was 12.56 W. The corresponding slope efficiency η_s was 40%. When output mirrors with transmissions of 2%, 5% and 10% were used, the laser threshold of pump power was 2.3 W, 1.36 W and 1.65 W, respectively. After comparison, the output performance with output mirror of 5% transmission is the best, so it is selected as the output mirror in the following investigations.

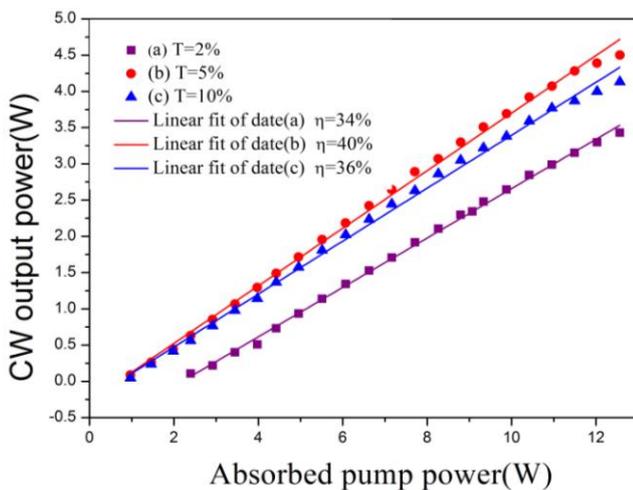


Fig. 2. Relationship of CW output power and absorbed pump power with output mirrors of varies transmission (color online)

Fig. 3 depicts the CW Nd:GGG laser output beam profiles at absorbed pump power of 2 W, 4 W and 6 W. It can be seen that the beam quality of Nd:GGG laser was good under low absorbed pump power. In contrast, the beam quality got worse at a high absorbed pump power. The beam quality factor (M^2) was obtained by a traveling knife-edge method. According to the Gaussian beam

propagation equation, the data were fitted and M^2 was found to be 12.3 and shown in Fig. 4. The beam quality could be improved significantly with a larger cavity length or using an 880 nm diode laser pumping into the upper level directly.

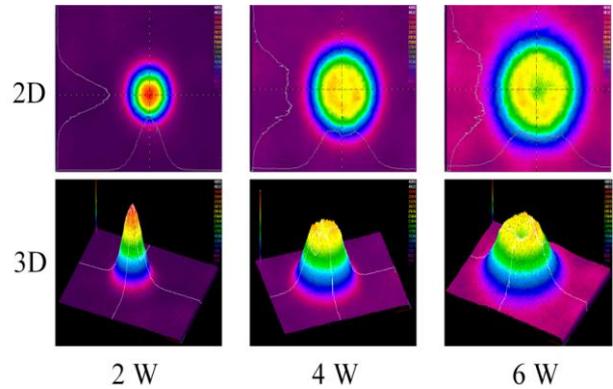


Fig. 3. Beam profiles of CW Nd:GGG laser at various absorbed pump power (color online)

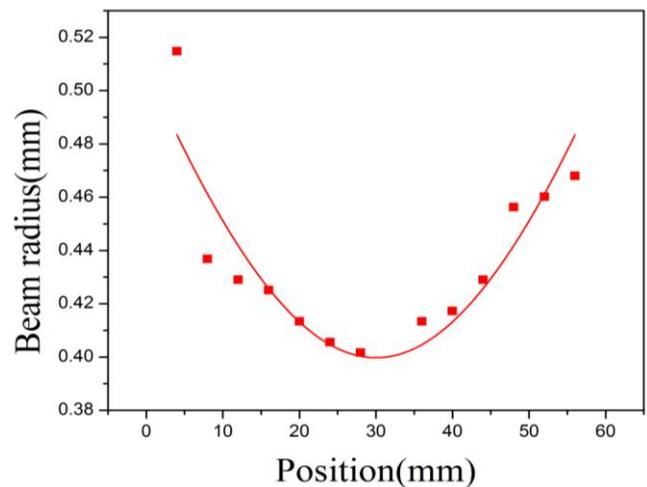


Fig. 4. The beam radius under output power of 4.5 W (color online)

In the passively Q-switched operation, $\text{Cr}^{4+}:\text{YAG}$ crystals with $T_0=85\%$ and $T_0=95\%$ were set between the Nd:GGG crystal and output couplers to investigate the output characteristics. The average output power, repetition rate, pulse width, single pulse energy and peak power were measured and displayed in Figs. 5-8, respectively. Fig. 5 depicted the average output power increased with the absorbed pump power. The maximum of average output power were 1.24 W and 1.56 W when the absorbed pump power was 5.9 W with the $\text{Cr}^{4+}:\text{YAG}$ crystals of $T_0=85\%$ and $T_0=95\%$, respectively.

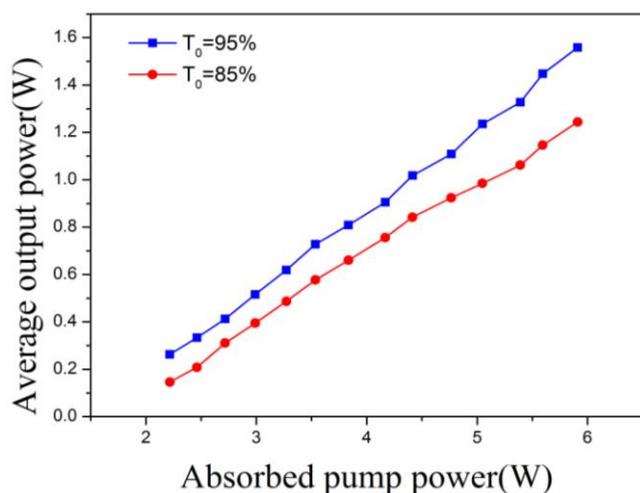


Fig. 5. Relationship of average output power and absorbed pump power (color online)

The repetition rate and pulse width were detected by a digital oscillograph and a high-speed Si-detector, respectively. Fig. 6 and Fig. 7 showed the results. From Fig. 6, it can be seen that the repetition rate increased by increasing the pump power. The maximum repetition rates of 6.7 kHz and 16.3 kHz were obtained under the absorbed pump power of 5.91 W when Cr⁴⁺:YAG crystals of $T_0=85\%$ and $T_0=95\%$ were selected, respectively. Fig. 7 showed that the pulse width decreased as the absorbed pump power increased. When the absorbed pump power was 5.6 W, the pulse widths were 28.7 ns and 29.3 ns for Cr⁴⁺:YAG crystals with the initial transmission of 85% and 95%, respectively.

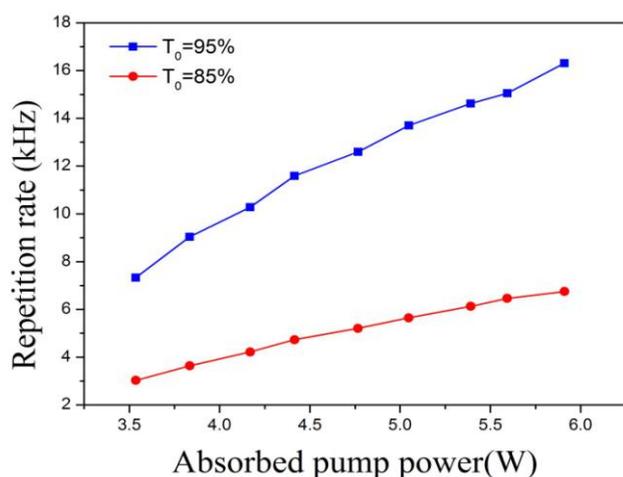


Fig. 6. Relationship of repetition rate and absorbed pump power (color online)

Fig. 8 showed the relationship between pulse energy, pulse peak power and absorbed pump power. The measured results indicated that both pulse energy and peak power increased slowly or got a fluctuation somewhere with increasing pump power. The pulse energy and peak power with Cr⁴⁺:YAG of $T_0=85\%$ were obviously higher than those with 95%. When the absorbed pump power

increased to 5.9 W, the pulse energy and the peak power with Cr⁴⁺:YAG of $T_0=85\%$ were 184 μJ and 6.44 kW respectively, which is much higher than those of 95 μJ and 3.28 kW for the initial transmission of 95%.

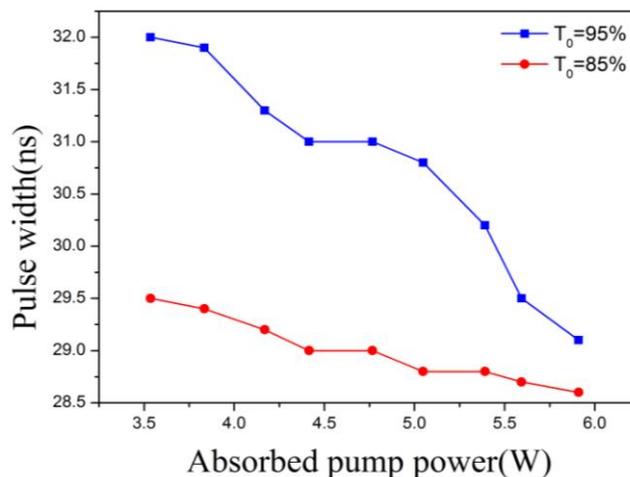


Fig. 7. Relationship of pulse width and absorbed pump power (color online)

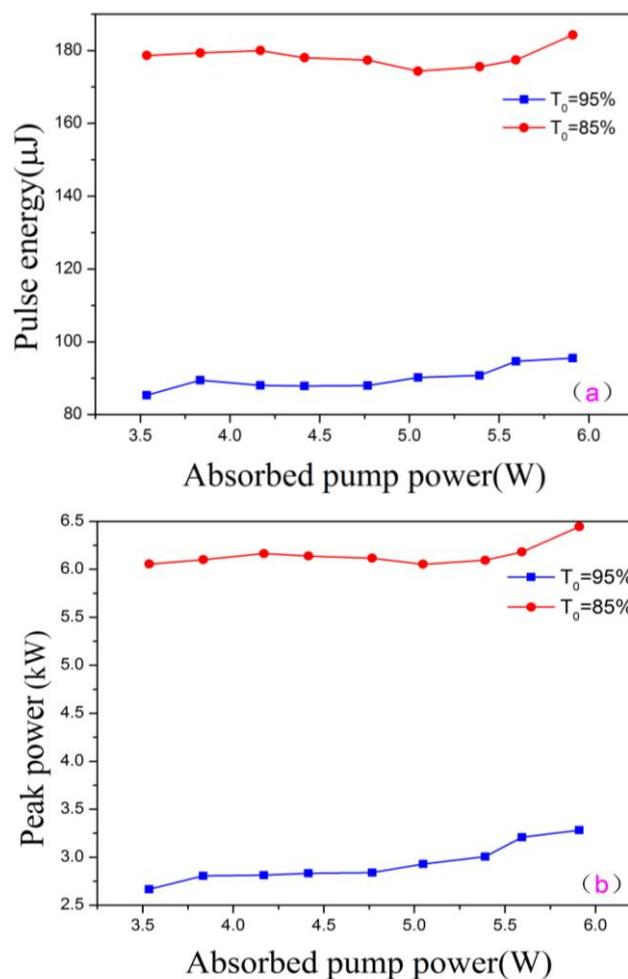


Fig. 8. Relationship of pulse performance and absorbed pump power: (a) pulse energy; (b) pulse peak power (color online)

4. Conclusions

In conclusion, we have demonstrated the performance of a diode-pumped CW and passively Q-switched 1.06 μm laser with a Nd:GGG crystal. The CW output power with varies output couplers was researched, and the maximum output power reached to 4.5 W when the absorbed pump power was 12.56 W. The laser beam quality factor (M^2) was measured under this condition, and was found to be 12.3 for vertical direction. The beam quality could be improved significantly with a larger cavity length or using an 880 nm diode laser pumping into the upper level directly. In the passively Q-switched operation, Cr^{4+} :YAG crystals with $T_0=85\%$ and $T_0=95\%$ were set between the Nd:GGG crystal and output couplers to investigate the output characteristics. Using Cr^{4+} :YAG crystal with $T_0=95\%$, the average output power, pulse width, repetition rate, single pulse energy and peak power were 1.24 W, 28.7 ns, 6.7 kHz, 184 μJ and 6.44 kW respectively when absorbed pump power was 5.9 W. And the corresponding results for Cr^{4+} :YAG crystal of $T_0=95\%$ were 1.56 W, 29.3 ns, 16.3 kHz, 95 μJ and 3.28 kW respectively.

Acknowledgments

This work was supported by the Science Research Foundation of Xijing University (Grant No. XJ18B09) and the Scientific Research Program Funded by Shaanxi Provincial Education Department (Program No. 18JC033).

References

- [1] Y. Ma, Y. He, P. Patimisco, A. Sampaolo, S. Qiao, X. Yu, F. K. Tittel, V. Spagnolo, *Appl. Phys. Lett.* **116**, 011103 (2020).
- [2] W. Strek, B. Cichy, L. Radosinski, P. Gluchowski, L. Marciniak, M. Lukaszewicz, D. Hreniak, *Light-Sci. Appl.* **4**(1), e237 (2015).
- [3] Y. Ma, Y. He, Y. Tong, X. Yu, F. K. Tittel, *Opt. Express* **26**(24), 32103 (2018).
- [4] Y. Ma, S. Qiao, P. Patimisco, A. Sampaolo, Y. Wang, F. K. Tittel, V. Spagnolo, *Appl. Phys. Lett.* **116**, 061101 (2020).
- [5] T. Kojima, S. Konno, S. Fujikawa, *Opt. Lett.* **25**, 105 (2000).
- [6] Y. F. Ma, X. Yu, H. J. Li, J. P. Lin, *Opt. Laser Technol.* **43**, 1491 (2011).
- [7] Y. F. Ma, X. Yu, F. K. Tittel, R. P. Yan, X. D. Li, C. Wang, J. H. Yu, *Appl. Phys. B* **107**, 339 (2012).
- [8] H. P. Peng, C. Yang, S. Lu, N. Ma, M. Chen, *Chin. Phys. B* **28**, 024205 (2019).
- [9] C. H. Zuo, H. Jia, B. T. Zhang, J. L. He, *Opt. Lett.* **13**, 021401 (2015).
- [10] Z. T. Jia, X. T. Tao, C. M. Dong, J. Zhang, H. J. Zhang, Z. P. Wang, M. H. Jiang, *Laser Phys. Lett.* **9**, 20 (2012).
- [11] B. Labranche, Q. Wu, P. Galarneau, *Proc. SPIE* **2041**, 326 (1998).
- [12] L. J. Qin, D. Y. Tang, G. Q. Xie, H. Luo, C. M. Dong, Z. T. Jia, H. H. Yu, X. T. Tao, *Opt. Commun.* **281**, 4762 (2008).
- [13] Y. Wan, D. Y. Zhu, Q. Y. Zeng, Z. Y. Zhang, J. Zhang, K. Han, *Chin. Phys. B* **14**, 714 (2005).
- [14] C. Feng, M. Liu, Y. B. Li, X. J. Gao, Z. Kang, G. S. Qin, Z. T. Jia, X. T. Tao, T. Song, Y. Y. Dun, F. Bai, P. Li, Q. P. Wang, J. X. Fang, *Appl. Phys. B* **123**, 81 (2017).
- [15] Y. F. Ma, X. Yu, X. D. Li, *Appl. Optics* **51**, 600 (2012).
- [16] X. Yu, C. Wang, F. Chen, R. P. Yan, Y. F. Ma, X. D. Li, J. B. Peng, *Laser Phys.* **21**, 442 (2011).
- [17] N. Pavel, T. Dascalu, G. Salamu, M. Dinca, N. Boicea, A. Birtas, *Opt. Express* **23**, 33028 (2015).
- [18] Y. F. Ma, H. J. Li, J. P. Lin, X. Yu, *Laser Phys.* **20**, 1802 (2010).
- [19] X. T. Yang, Y. L. Mu, N. B. Zhao, *Opt. Laser Technol.* **107**, 398 (2018).
- [20] J. J. Liu, C. Zhang, Y. Q. Zu, X. W. Fan, J. Liu, X. S. Guo, X. B. Qian, L. B. Su, *Laser Phys. Lett.* **15**, 045803 (2018).
- [21] R. Feldman, Y. Shimony, Z. Burshtein, *Opt. Mater.* **24**, 393 (2003).
- [22] Y. Ma, Z. Peng, Y. He, X. D. Li, R. P. Yan, X. Yu, Q. L. Zhang, S. J. Ding, D. L. Sun, *Laser Phys. Lett.* **14**, 085801 (2017).
- [23] Y. He, Y. F. Ma, J. Li, X. D. Li, R. P. Yan, J. Gao, X. Yu, R. Sun, Y. P. Pan, *Opt. Laser Technol.* **81**, 46 (2016).

*Corresponding author: mayf2010@163.com