DOI 10.1007/s10946-023-10176-0
Journal of Russian Laser Research, Volume 44, Number 6, November, 2023

EFFICIENT CONTINUOUS-WAVE DEEP-RED Pr : YLF LASER DOUBLE-PASS-PUMPED BY A FIBER-COUPLED BLUE LASER DIODE

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Abstract

We present an efficient continuous-wave deep-red Pr : YLF laser with a double-pass-pumping architecture. The fiber-coupled blue laser diode is used as the pump source. With an incident pump power of 15.3 W, the deep-red Pr : YLF laser reaches the 5.02 W output power at 720.8 nm, corresponding to a slope efficiency of 40.2%. In addition, we estimate the beam quality factor to be about 2.0.

Keywords: solid-state laser, deep-red laser, diode pumping, Pr : YLF.

1. Introduction

High-power continuous-wave (CW) visible lasers have many potential technical applications, such as optical information processing, precision measurement, bio-photonics, etc. [1–3]. In addition, they also produce ultraviolet radiation by one-step second-harmonic generation (SHG) [4]. The Rare-Earth Praseodymium (Pr) ion has many emission peaks in the visible spectral range [5], indicating efficient visible lasing in Pr-doped materials. The Pr : YLF crystal is an excellent gain medium for the visible light generation, owing to is long upper-level lifetime. In the past few years, green, orange, and red lasers based on Pr : YLF crystal have been reported with the blue-laser-diode (LD) pumping [6–10]. The maximum output power equal to 6.7 W at 640 nm was demonstrated with a single-emitter-diode pumping structure [10]. For deep-red lasers, to the best of our knowledge, the maximum output power equal to 5.01 W at 720.9 nm was reported in the Pr : YLF laser with a pumping of 24 W blue LD array [11]. The slope efficiency was 44% with respect to the absorbed pump power. The beam quality factors M^2 in x and y directions were 2.78 and 2.55, respectively. With the same pump structure, Liu et al. reported a 718.5 nm Pr : YLF laser with an output power of 1.45 W [12].

Compared with single-emitter-diode pumping, fiber-coupled LD pumping structure can suppress thermal aberration in the laser crystal, which is beneficial for improving the output power and beam quality [10,13,14]. There is not many report on the deep-red Pr : YLF laser pumped by the fiber-coupled blue LD. In 2020, He et al. demonstrated a 720.9-nm Pr : YLF laser single-end-pumped by a fiber-coupled blue LD [15]. An output power of 3.03 W and a slope efficiency of 30.04% were obtained.

In this paper, we demonstrate an efficient and high-power deep-red Pr : YLF laser, using the double-pass-pumping structure. We achieve the maximum output power equal to 5.02 W at 720.8 nm at an incident pump power of 15.3 W corresponding to a slope efficiency of 40.2%. The M^2 factor is measured to be about 2.0.

Manuscript submitted by the authors in English on October 7, 2023.

2. Experimental Setup

In Fig. 1, we show the schematic of the deep-red Pr : YLF laser double-pass-pumped by the blue LD. The pump source is a fiber-coupled LD with a maximum output power of about 15 W and a central wavelength of 444 nm, which matches well with the absorption peak of the Pr : YLF crystal. The core diameter and numerical aperture NA of the pigtail fiber are 200 μm and 0.22, respectively. The blue LD is mounted on a Copper heat sink, which is cooled at 25°C by circulated water. As the gain medium, we employ the *a*-cut Pr : YLF crystal with dimensions of 3×3 mm (in section)×12 mm (in length) and a doping concentration of 0.3 at.%. Two end-faces of laser crystal are coated with high transmission for both 444 and 720 nm. The Pr : YLF crystal is wrapped with an Indium foil and placed in a Copper heat sink. The operating temperature is controlled at 15°C by a homemade thermoelectric cooler. A telescope system consisting of two lenses, F1 and F2, with focal lengths of 20 and 40 mm, is used for focusing the pump light into the laser crystal, resulting in a 400 μm pump diameter. A mirror M is used to reflect residual pump light, and the other lens F2 is used to collimate and re-focus the pump beam into the laser crystal. We measure the single-pass pump absorption of the laser crystal to be about 68%, resulting in near 90% double-pass pump absorption.

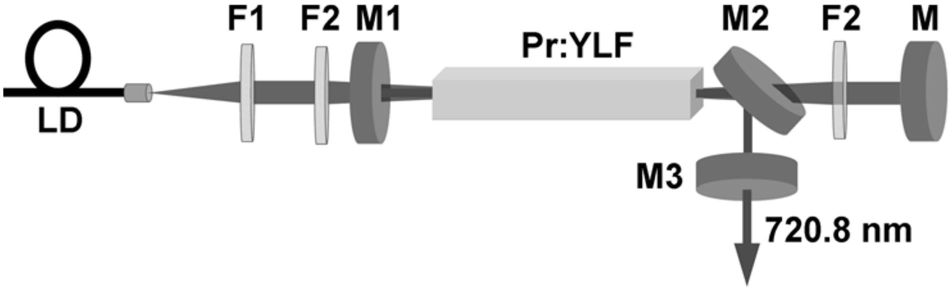

Fig. 1. Experimental setup of the deep-red Pr : YLF laser double-pass-pumped by a blue LD.

The folded cavity consists of a 0° dichromic mirror M1, a 45° dichromic mirror M2, and an output coupler M3. Mirrors M1 and M2 are coated with high transmission for 444 nm and high reflective for 720 nm that is used to separate the deep-red light and pump light. Mirror M3 is a plano-concave mirror; to avoid the 640-nm oscillating wavelength, mirror M3 is also coated with high transmission of more than 70% at 640 nm.

3. Experimental Results

In this work we use a power meter (Thorlabs 425C) to record the output powers. First, output transmittances of 2.1% and 4.8% are employed to measure the output characteristics of the deep-red Pr : YLF laser; see Fig. 2. When the radius of curvature of the output coupler is 50 mm, we achieve the maximum output power equal to 1.92 W at an incident pump power of 7.9 W, corresponding to a slope efficiency of 29.6%. With an output transmittance of 4.8%, the output power slightly decreases to 1.78 W at same pump power, corresponding to a slope efficiency of 31.4%. A high slope efficiency is more suitable to obtain the high output power, so the 4.8% output transmittance can be used in the experiment under high-pump-power conditions.

At an output transmittance of 4.8%, we use three radii of curvature of the output coupler to optimize

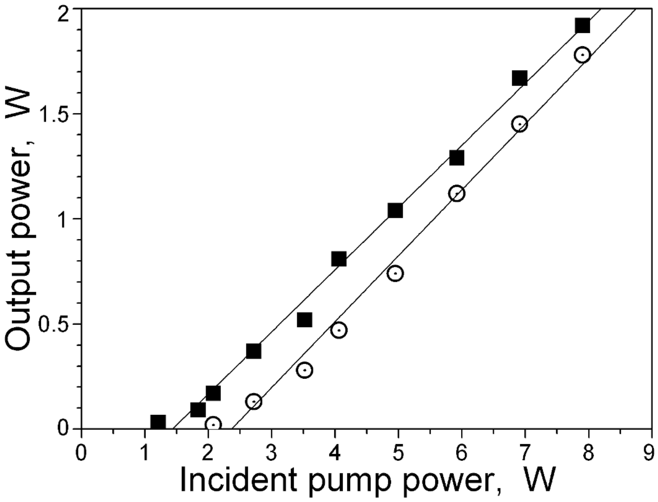

Fig. 2. Output characteristics of the deep-red Pr : YLF laser with output transmissions of 2.1% (■, $\eta = 29.6\%$) and 4.8% (⊙, $\eta = 31.4\%$).

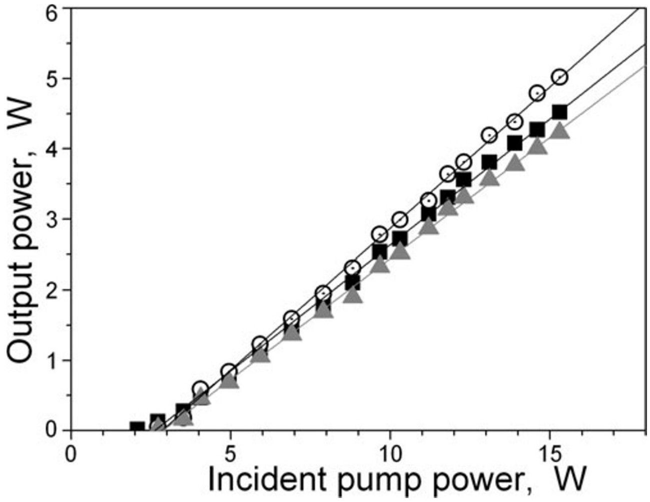

Fig. 3. Output characteristics of the deep-red Pr : YLF laser at $T = 4.8\%$ with radii of curvature 50 mm (■, $\eta =$ 35.7%), 100 mm (⊙, $\eta = 35.7\%$), and 150 mm (▲, $\eta =$ 35.7%).

the output characteristics of the deep-red Pr : YLF laser; see Fig. 3. With a radius of curvature of 50 mm and an incident pump power of 15.3 W, the output power reaches 4.52 W, corresponding to a slope efficiency of 35.7%. Increasing the radius of curvature to 100 mm, we achieve the maximum output power equal to 5.02 W at the same pump power, corresponding to a slope efficiency of 40.2%. If the radius of curvature us equal to 150 mm, the output power decreases to 4.23 W at the same pump power.

We use a spectrometer (APE wavescan) to record the output spectrum of the deep-red Pr : YLF laser; see Fig. 4. The central wavelength is located at 720.8 nm. No obvious shifts are measured under different output transmittances and pump powers.

The beam quality factor M^2 is measured by the 90/10 knife-edge method. A lens with a focal length of 100 mm is used to transform the deep-red laser beam. The beam radii at different positions are measured

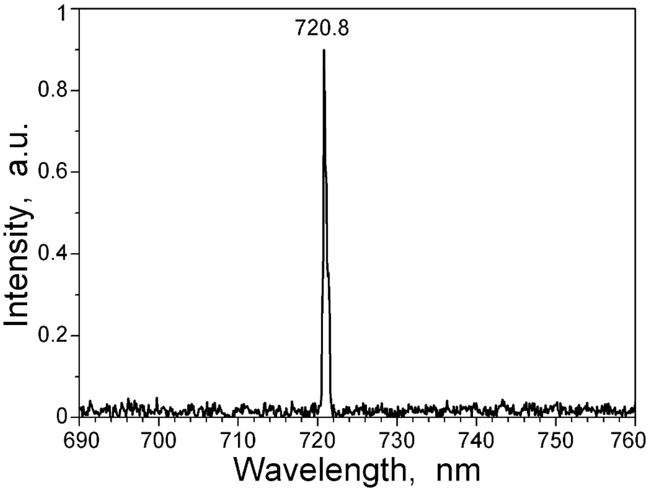

Fig. 4. Output spectrum of the deep-red Pr : YLF laser at the maximum output power.

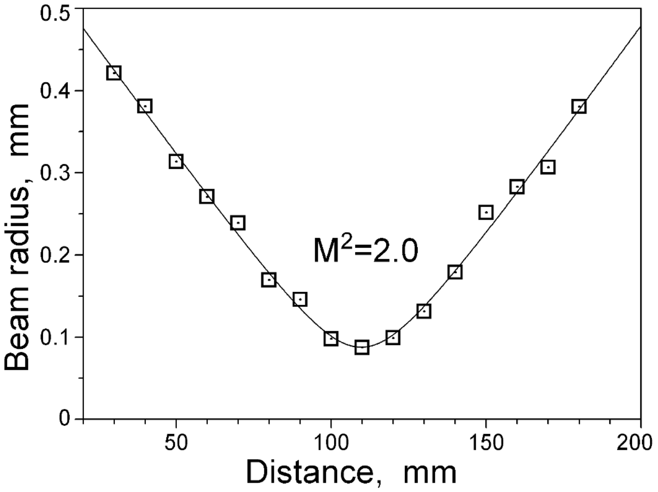

Fig. 5. M^2 measurement of the deep-red Pr : YLF laser at the maximum output power.

along the beam propagation direction; see Fig. 5. By fitting the Gauss beam-propagation equation, we estimate the M^2 factor to be about 2.0.

4. Summary

We designed and demonstrated an efficient deep-red CW Pr : YLF laser double-pass-pumped by a fiber-coupled blue LD. We achieved the maximum output power equal to 5.02 W at 720.8 nm and at an incident pump power of 15.3 W. The slope efficiency was 40.2%. Using the 90/10 knife-edge method, we measured the M^2 factor to be about 2.0; in addition, no power saturation was presented. We believe that the deep-red Pr : YLF laser holds the potential for power scaling under high pump levels.

Acknowledgments

This work was supported by the Natural Science Foundation of Heilongjiang Province under Grant No. LH2022F041 and Harbin University Doctoral Foundation under Grant No. HUDF2023207.

References

1. L. Tong, T. Pakizeh, L. Feuz, and A. Dmitriey, *Sci. Rep.*, **3**, 2311 (2013).
2. L. Peng, F. Qin, C. Wang, et al., *Opt. Lett.*, **48**, 4061 (2023).
3. E. Balanikas, A. Banyasz, G. Baldacchino, and D. Markovitsi, *Molecules*, **24**, 2347 (2019).
4. Y. Zhang, J. Zou, W. Zheng, et al., *Chin. Opt. Lett.*, **19**, 091406 (2021).
5. L. Esterowitz, F. J. Bartoli, R. E. Allen, et al., *Phys. Rev. B*, **19**, 6442 (1979).
6. S. Luo, X. Yan, Q. Cui, et al., *Opt. Commun.*, **380**, 357 (2016).
7. M. Demesh, D. Marzahl, A. Yasukevich, et al., *Opt. Lett.*, **42**, 4687 (2017).
8. N. Li, B. Xu, S. Cui, et al., *IEEE Photonics Technol. Lett.*, **31**, 1457 (2019).
9. M. Badtke, H. Tanaka, S. Kalusniak, et al., *Appl. Phys. Express*, **15**, 082006 (2022).
10. H. Tanaka, S. Fujita, and F. Kannari, *Appl. Opt.*, **57**, 5923 (2018).
11. R. Fang, R. Huang, H. Xu, et al., *Opt. Laser Technol.*, **164**, 109487 (2023).
12. X. Liu, Z. Li, C. Shi, et al., *Laser Phys.*, **32**, 025801 (2022).
13. X. Duan, J. Wu, Y. Ding, et al., *Opt. Laser Technol.*, **158**, 108929 (2023).
14. J. Wu, Y. Ju, X. Duan, et al., *Opt. Laser Technol.*, **158**, 108845 (2023).
15. M. He, S. Chen, Q. Na, et al., *Chin. Opt. Lett.*, **18**, 011405 (2020).