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High-efficiency Nd:$LuVO_4$ laser at 1343 nm recycling-pumped by a laser diode at 916 nm

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A high-efficiency Nd:$LuVO_4$ laser, pumped by a fiber-coupled laser diode at 916 nm, was successfully demonstrated. Employing a recycling-pumping architecture, an output power of 12.1 W at 1,343.2 nm was achieved with an incident pump power of 20 W, resulting in a slope efficiency of 62.1% and an optical conversion efficiency of 60.5%. Furthermore, the beam quality factor was measured to be approximately 1.1 at the maximum output level.

KEYWORDS

diode-pumped lasers, Nd lasers, in-band pump, recycling-pump, Nd:LuVO4

1 Introduction

The 1.3 μm diode-pumped solid-state laser has garnered significant attention in various technical applications, including medical and spectroscopy. The transition from $^4F_{3/2}$ to $^4I_{13/2}$ of Nd ions represents an outstanding method for generating high-performance 1.3 μm laser radiation. The conventional Nd:YAG crystal has been extensively employed in diode-pumped lasers operating at 1.3 μm [1–3]. Nd-doped vanadate crystals are distinguished by their substantial absorption and emission cross-sections. Consequently, Nd:YVO_4 and Nd:$GdVO_4$ crystals represent popular options for producing 1.3-μm laser [4–8]. However, the quantum defect of 39.7% between pump and laser photons constrains the enhancement of output performance of Nd lasers at 1.3 μm. One potential solution involves utilizing a pump wavelength close to 880 nm, enabling the pump photon to directly excite the Nd ions to transition to the laser upper level (4F3/2). This technique, known as in-band pumping technology, leads to a reduced quantum defect and increased efficiency [9–11]. In 2005, researchers demonstrated a Nd:YAG laser operating at a wavelength of 1,341 nm. The laser was pumped by a LD at 885 nm and achieved a slope efficiency of 45% [12]. Similarly, in the same year, a continuous-wave (CW) Nd:$GdVO_4$ laser operating at 1,341 nm was reported, achieving a slope efficiency of 60% under the pumping of an 879 nm Ti:Sapphire laser [13]. In 2008, a Nd:YVO_4 laser operating at 1,342 nm was demonstrated using a Q-switched Ti: Sapphire laser at 879 nm [14]. Moving forward to 2010, researchers demonstrated a CW Nd:YLF laser operating at 1,321 nm. The laser had an output power of 3.6 W and a slope efficiency of 52%. It was achieved using a fiber-coupled LD at 880 nm [15]. In 2018, the 1.3-μm lasing performances of Nd:$Gd_{0.69}Y_{0.3}TaO_4$ and Nd:$Gd_{0.68}Y_{0.3}NbO_4$ mixed crystals were investigated under 879-nm LD pumping [16].

The Nd:$LuVO_4$ crystal exhibits larger absorption and emission cross sections compared to Nd:YVO4 and Nd:$GdVO_4$, making it a suitable choice for use as the laser medium in the near-infrared spectral region. Nd:$LuVO_4$ lasers operating at 0.9 μm, 1.06 μm, and 1.3 μm wavelengths have been reported, utilizing laser diode (LD) pumping near 808 nm [17–19].

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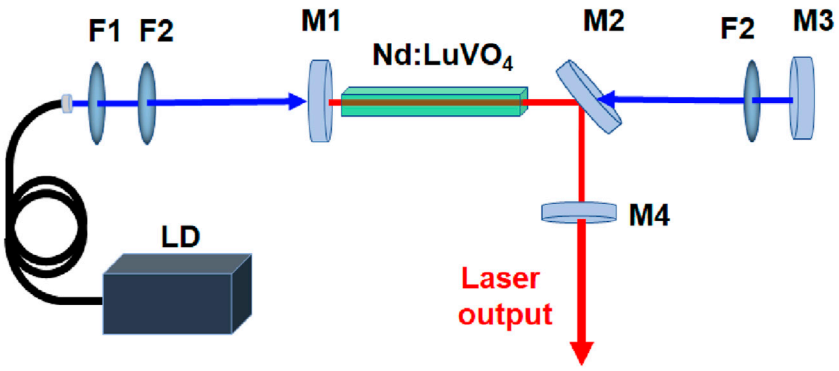

FIGURE 1
The schematic diagram of Nd:$LuVO_4$ laser at 1,343 nm recycling-pumped at 916 nm.

In 2010, Nd:$LuVO_4$ lasers achieved output powers of 7.0 W and 6.2 W at 1,343 nm when pumped at 880 nm and 809 nm, corresponding to the slope efficiencies of 44.5% and 34.9% with respect to absorbed pump power, respectively [20]. In addition to the absorption peaks at 809 nm and 880 nm, the Nd:$LuVO_4$ crystal also exhibits a significant absorption peak at 916 nm. By utilizing this absorption peak for pumping, the quantum defect in Nd:$LuVO_4$ lasers operating at 1,343 nm can be reduced to 31.8%. This reduction results in higher efficiency and lower thermal loading for the laser system. In 2013, a Nd:$LuVO_4$ laser pumped by a diode-pumped 916-nm Nd:$LuVO_4$ laser achieved an output power of 1.12 W at 1,343 nm. This corresponds to a slope efficiency of 61.9% relative to the absorbed pump power [21].

In this paper, to the best of our knowledge, a high-efficiency Nd:$LuVO_4$ laser at 1,343 nm that is recycling-pumped by a fiber-coupled LD at 916 nm was demonstrated. By utilizing this approach, we achieved the maximum output power of 12.1 W at 1,343.2 nm, with an incident pump power of 20 W. This corresponds to a slope efficiency of 62.1% and an optical conversion efficiency of 60.5%. Furthermore, the beam quality factor (M^2) was estimated to be approximately 1.1 at maximum output power.

2 Experimental setup

The experimental setup of a diode-pumped Nd:$LuVO_4$ laser with a recycle pumping scheme was shown in Figure 1. The pump source utilized in the experiment was a wavelength-locked fiber-coupled LD with a maximum output power of 20 W at 916 nm. The pigtail fiber had a core diameter of 105 μm and a numerical aperture of 0.22. To focus the pump beam into the Nd:$LuVO_4$ crystal, a telescope comprising lenses F1 and F2 was employed, with focal lengths of 15 mm and 60 mm, respectively, resulting in a pump spot radius of 210 μm. A c-cut Nd:$LuVO_4$ crystal with a doping concentration of 1.0 at.% and dimensions of 3 × 3 (in cross-section) ×10 (in length) mm^3 was used in the experiment. Both surfaces of the crystal were antireflection coated from 900 nm to 1,400 nm. The crystal, wrapped in indium foil, was mounted in a copper heatsink, with the operating temperature maintained at 18 °C using a thermoelectric cooler. The single-pass pump absorption of the Nd:$LuVO_4$ crystal was measured to be approximately 80% under nonlasing conditions.

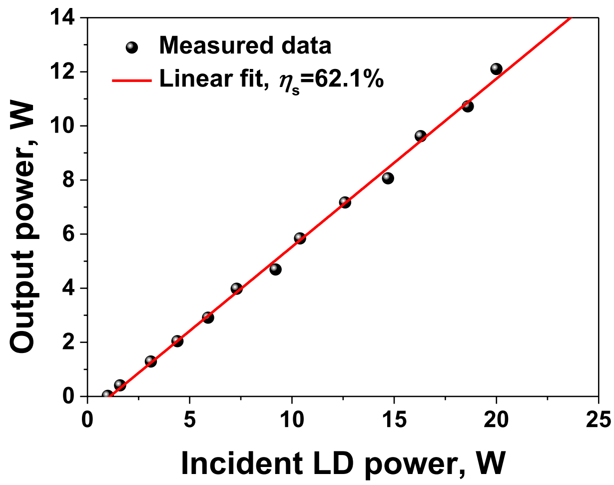

FIGURE 2
The output power of Nd:$LuVO_4$ laser *versus* incident pump power at 916 nm.

The laser cavity consists of three mirrors. To achieve a lasing wavelength of 1,343 nm, the flat M1 mirror was coated with high transmission at wavelengths of 916 nm and 1,066 nm, as well as high reflectivity at the lasing wavelength of 1,343 nm. The M2 mirror was a flat 45° dichromatic mirror with high transmission at 916 nm and high reflectivity at 1,343 nm. In the experiment, an output coupler M4 with a plano-concave shape and a radius of curvature of 200 mm was used, with an output transmittance of 25%. The physical length of the cavity was approximately 50 mm. The flat M3 mirror, which had high reflectivity at 916 nm, and another lens F2 were utilized to achieve pump recycling.

3 Experimental results

Figure 2 displays the output powers of the Nd:$LuVO_4$ laser, which were measured using a Coherent PM 30 power meter.

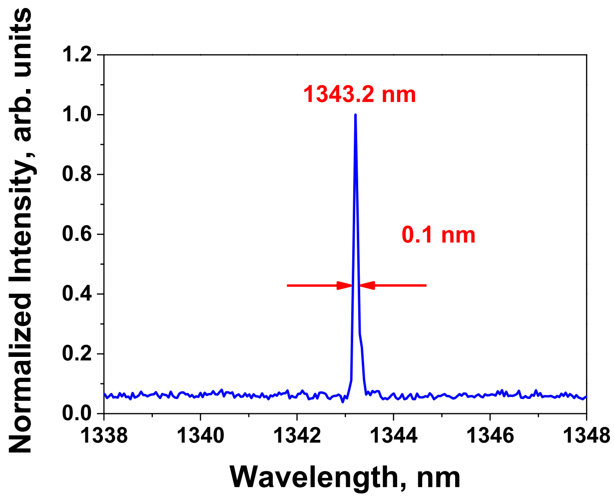

FIGURE 3
The output spectrum of $Nd:LuVO_4$ laser pumped at 916 nm.

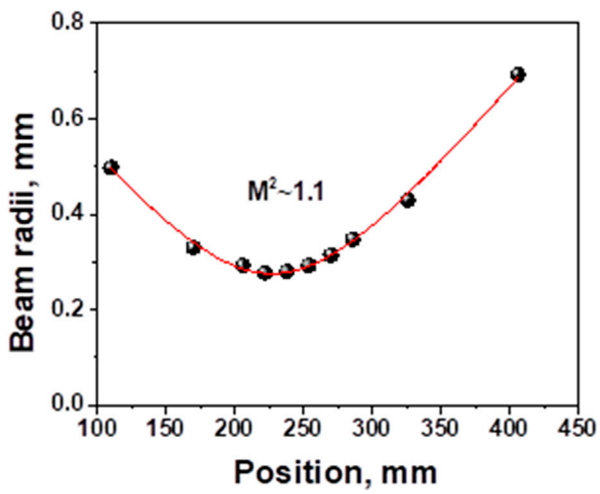

FIGURE 4
Measurement of beam quality factor of $Nd:LuVO_4$ laser pumped at 916 nm.

With an LD pump at 916 nm, a maximum output power of 12.1 W was achieved under an incident LD power of 20 W, resulting in a slope efficiency of 62.1% and an optical conversion efficiency of 60.5%. The pump threshold for the laser was approximately 1.0 W. In addition, the power fluctuation was about 2.1% within a period of 1 hour. Higher temperature-control accuracy and narrower output linewidth can improve the power stability. Limiting the pump power, more high output power was not presented in this work. No power saturation phenomenon was observed in Figure 2. We believe that output power could be increased under higher pump level. Furthermore, optimizing the overlap between pump and oscillating beams and output transmittance could further improve output performance.

The output spectra of $Nd:LuVO_4$ laser were recorded by a laser spectrum analyzer (Bristol, 771B). As depicted in Figure 3, a single oscillating line at 1,343.2 nm was observed, with an FWHM linewidth of approximately 0.1 nm. Throughout the increase in pump power from threshold to maximum level, no other wavelengths were detected.

The beam quality factor of $Nd:LuVO_4$ laser was measured by the 90/10 knife-edge method, as shown in Figure 4. The estimated value at maximum output power was approximately 1.1. Furthermore, images of the far-field beam in both 2D and 3D were captured using a camera (Ophir-spricon, Pyrocam IV), as illustrated in Figure 5. These images clearly indicate that the beam exhibits a TEM_{00} Gaussian profile.

4 Conclusion

In conclusion, this work presents the successful demonstration of an efficient recycling-pumped $Nd:LuVO_4$ laser, achieved using a wavelength-locked fiber-coupled LD at 916 nm. The laser attained a maximum output power of 12.1 W at 1,343.2 nm with an incident pump power of 20 W, resulting in a slope efficiency of 62.1% and an optical conversion efficiency of 60.5%. Furthermore, the M^2-factor at maximum output level was measured to be approximately 1.1. These results highlight promising prospects for enhancing the output power at 1,343 nm for the $Nd:LuVO_4$ laser.

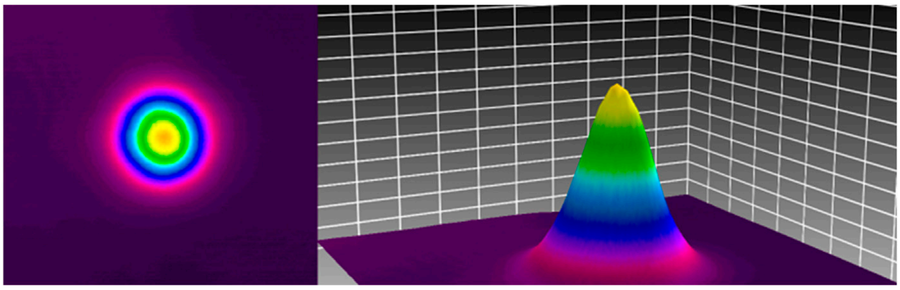

FIGURE 5
The 2D and 3D beam profile of $Nd:LuVO_4$ laser with maximum output power.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

WD: Writing–original draft, Data curation, Writing–review and editing. TL: Investigation, Supervision, Writing–review and editing. YD: Investigation, Methodology, Writing–original draft. YuZ: Data curation, Formal Analysis, Writing–review and editing. YoZ: Methodology, Validation, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The handling editor XD declared a past Authorship with one of the authors YD.

Publisher's note

References

1. Hall GJ, Ferguson AI. Generation of single-frequency radiation at 1064, 1319, and 659.5 nm with an all-solid-state, out-of-plane Nd: YAG ring laser. *Opt Lett* (1994) 19(8): 557–9. doi:10.1364/ol.19.000557

2. Guo R, Hong FL, Onae A, Bi ZY, Matsumoto H, Nakagawa K. Frequency stabilization of a 1319-nm Nd: YAG laser by saturation spectroscopy of molecular iodine. *Opt Lett* (2004) 29(15):1733–5. doi:10.1364/ol.29.001733

3. Liu H, Gong M, Wushouer X, Gao S. Compact corner-pumped Nd: YAG/YAG composite slab 1319 nm/1338 nm laser. *Laser Phys Lett* (2010) 7(2):124–9. doi:10.1002/lapl.200910124

4. Sennaroglu A. Efficient continuous-wave operation of a diode-pumped Nd:YVO_4 laser at 1342 nm. *Opt Commun* (1999) 164(4-6):191–7. doi:10.1016/s0030-4018(99)00195-9

5. Zhao S, Huang HT, He JL, Zhang BT, Yang JF, Xu JL, et al. An efficient and compact diode end-pumped Nd: YVO_4 slab laser. *Laser Phys Lett* (2009) 6(8):571–4. doi:10.1002/lapl.200910044

6. Ogilvy H, Withford MJ, Dekker P, Piper J. Efficient diode double-end-pumped Nd: YVO_4 laser operating at 1342nm. *Opt Express* (2003) 11(19):2411–5. doi:10.1364/oe.11.002411

7. Du C, Ruan S, Zhang H, Yu Y, Zeng F, Wang J, et al. A 13.3-W laser-diode-array end-pumped Nd: $GdVO_4$ continuous-wave laser at 1.34 µm. *Appl Phys B* (2005) 80: 45–8. doi:10.1007/s00340-004-1687-z

8. Du C, Qin L, Meng X, Xu G, Wang Z, Xu X, et al. High-power Nd: $GdVO_4$ laser at 1.34 µm end-pumped by laser-diode-array. *Opt Commun* (2002) 212(1-3):177–81. doi:10.1016/s0030-4018(02)01978-8

9. Pavel N, Kränkel C, Peters R, Petermann K, Huber G. In-band pumping of Nd-vanadate thin-disk lasers. *Appl Phys B* (2008) 91:415–9. doi:10.1007/s00340-008-3013-7

10. Duan X, Wu J, Ding Y, Yang X, Dai T. Electro-optically Q-switching of dual-diode-pumped Ho-doped lutetium vanadate laser. *Opt Laser Technol* (2023) 158: 108929. doi:10.1016/j.optlastec.2022.108929

11. Wu J, Ju Y, Duan X, Yan R, Ding Y, Yan D, et al. Electro-optically Q-switching performance of diode-pumped Ho: $GdVO_4$ laser at 2.05 µm. *Opt Laser Technol* (2023) 158:108845. doi:10.1016/j.optlastec.2022.108845

12. Pavel N, Lupei V, Taira T. 1.34-µm efficient laser emission in highly-doped Nd: YAG under 885-nm diode pumping. *Opt Express* (2005) 13(20):7948–53. doi:10.1364/opex.13.007948

13. Saikawa J, Sato Y, Taira T, Nakamura O, Furukawa Y. Efficient 1341-nm laser emission and heat generation characteristics in Nd:$GdVO_4$ laser under direct 879-nm pumping. In: *Advanced solid-state Photonics*. Optica Publishing Group (2005). p. MB48. doi:10.1364/ASSP.2005.MB48

14. Ding X, Zhang H, Wang R, Wen WQ, Wang P, Yao JQ, et al. High-efficiency direct-pumped Nd:YVO_4 laser operating at 1.34 µm. *Opt Express* (2008) 16(15): 11247–52. doi:10.1364/oe.16.011247

15. Lü YF, Xia J, Zhang XH, Zhang AF, Wang JG, Bao L, et al. High-efficiency direct-pumped Nd:YLF laser operating at 1321 nm. *Appl Phys B* (2010) 98:305–9. doi:10.1007/s00340-009-3792-5

16. Yan RP, Zhao C, Li X, Li K, Yu X, Yao W, et al. Investigation on 1.3 µm laser performance with Nd:$Gd_{0.69}Y_{0.3}TaO_4$ and Nd:$Gd_{0.68}Y_{0.3}NbO_4$ mixed crystals. *Opt Express* (2018) 26(12):15785–92. doi:10.1364/oe.26.015785

17. Zhang C, Zhang L, Wei Z, Long Y, Zhang Z, Zhang Z, et al. Diode-pumped continuous-wave Nd: $LuVO_4$ laser operating at 916nm. *Opt Lett* (2006) 31(10):1435–7. doi:10.1364/ol.31.001435

18. Maunier C, Doualan JL, Moncorgé R, Speghini A, Bettinelli M, Cavalli E. Growth, spectroscopic characterization, and laser performance of Nd:$LuVO_4$ a new infrared laser material that is suitable for diode pumping. *JOSA B* (2002) 19(8):1794–800. doi:10.1364/josab.19.001794

19. Zhang H, Liu J, Wang J, Xu X, Jiang M. Continuous-wave laser performance of Nd:$LuVO_4$ crystal operating at 1.34 µm. *Appl Opt* (2005) 44(34):7439–41. doi:10.1364/ao.44.007439

20. Lü YF, Zhang XH, Chen JF, Sun G, Zhao Z. All-solid-state Nd:$LuVO_4$ laser operating at 1066 nm and 1343 nm under diode pumping into the emitting level. *Laser Phys Lett* (2010) 7(10):699–702. doi:10.1002/lapl.201010045

21. Bao L. A high efficiency 1343 nm Nd: $LuVO_4$ laser in-band pumped at 916 nm. *Laser Phys* (2013) 23(8):085003. doi:10.1088/1054-660x/23/8/085003