Highly-efficient, dual-wavelength Nd:YLF laser emitting at 1314 nm and 1047 nm

Felipe Maia Prado
Center of Lasers and Applications
Nuclear and Energy Research Institute
São Paulo, Brazil
https://orcid.org/0000-0001-9350-2496

Tomás Junqueira Franco
Department of Physics
RWTH Aachen University
Aachen, Germany
https://orcid.org/0009-0001-3225-2080

Niklaus Ursus Wetter
Center of Lasers and Applications
Nuclear and Energy Research Institute
São Paulo, Brazil
https://orcid.org/0000-0002-9379-9530

2023 International Conference on Optical MEMS and Nanophotonics (OMN) and SBFoton International Optics and Photonics Conference (SBFoton IOPC) | 979-8-3503-0402-2/23/$31.00 ©2023 IEEE | DOI: 10.1109/OMN/SBFOTONIOPC58971.2023.10230922

***Abstract*: We report a record optical-to-optical efficiency of 43% and a slope efficiency of 48% for a Nd:YLF laser emitting at 1314 nm. The crystal was side-pumped by a VBG-equipped diode emitting at 797 mn, with a peak power of 1545 W. We also report simultaneous dual-wavelength emission, at 1313 nm and 1047 nm.**

Keywords: Nd:YLF, Solid-state laser, Bichromatic emission, Dual-wavelength, 1313 nm, 1047 nm.

I. INTRODUCTION

Neodymium lasers are well known for their emissions in the 1 µm region, with emission lines at 1064 nm for Nd:YAG and Nd:YVO crystals and at 1053 nm (σ) and 1047 nm (π) for Nd:YLF [1-3]. These laser lines have emission cross-sections up to nine times higher than the transitions at 1.3 µm [4]. Although crystals such as Nd:YAG and Nd:YVO exhibit higher cross-sections at 1.3 µm when compared to Nd:YLF, they suffer from a stronger thermal lensing and lower lifetime duration [4-7]. With an upper state lifetime twice as long as Nd:YAG (230 µs), or even five times that of Nd:YVO (95 µs), Nd:YLF (480 µs) is particularly suited for high power Q-switch applications, especially in a side pumping scheme for improved pump absorption, reduced thermal lensing, and increased output power [5-9]. Additionally, only Nd:YLF emits at 1.31 µm, while Nd:YAG and Nd:YVO emit at 1.34 µm.

Nd:doped crystals can exhibit simultaneous multiple-wavelength lasing behavior, a property that can generate two or more fundamental laser emissions from a single crystal [8,10]. This can be of use in a variety of applications such as spectroscopy, remote sensing, and holography [8,10,11]. This phenomenon can also be of interest for second-harmonic generation (SHG), sum frequency generation (SFG), and in THz applications [1,10-12]. Demonstrations of these phenomena have been observed for nearby emissions, such as the 1047 nm and 1053 nm in Nd:YLF, and more distant transitions, including the 1064 nm and 946 nm and the 1064 nm and 1342 nm in Nd:YAG [1, 8,11,3].

The first recorded dual-wavelength emission of a Nd:YLF crystal, at 1.05 µm and 1.31 µm, was in 1983 [13]. However, as a lamp pumping scheme was utilized, the laser was only capable of wielding an efficiency of 0.7%. Today, with the wide use of diode lasers as pumping sources and technologies such as volume Bragg gratings (VBG), to narrow the diode emissions, it is possible to achieve Nd:YLF laser operation at the 1 µm region with 68% slope efficiency, when pumped at 797 nm [14–18], and 78% efficiency when direct pumped at 863 nm [6,19]. Despite the lower cross-section of the 1.3 µm region, slope efficiencies as high as 54% has been achieved with an optical-to-optical efficiency of 34% [5]. This continuous efficiency-improvement holds great significance, as they can drastically diminish operating costs by reducing cooling requirements and providing a longer lifespan for the laser and its components [6, 14, 17].

Funding: FAPESP nº 2022/15276-0; 2017/10765-5. CNPQ nº 308526 2021-0; INCT nº 465.763/2014 and 302532/2019-6.

In this paper, we present a compact Nd:YLF laser that can selectively emit, by cavity alignment, at either 1314 nm, 1047 nm, or a simultaneous combination of both wavelengths. When operating at 1314 nm, the laser reached record values of optical-to-optical efficiency.

II. EXPERIMENTAL SET-UP

A 13x13x3 mm^3, a-cut, Nd:YLF crystal (Crystech, China), with 1 mol% Nd^{3+} doping, was side pumped by a VBG-equipped 12-bar diode stack (Northrop Grumman, US). The peak pump power was measured to be 1544.8 ± 8.8 W with a repetition rate of 5 Hz and a pulse width of 350 µs, resulting in an average power of 2.7 W. The low duty cycle (~0.17%) of the diode was set by the manufacturer to maintain the 797 nm emission line at a measured linewidth of 0.92 ± 0.03 nm (FWHM) and helped to avoid thermal lensing.

The bounce laser cavity employed a plane mirror (PM), with transmissions of $T_{@1314nm}$=10% and $T_{@1047nm}$=98%, and a concave mirror (CM) of 8 m radius of curvature ($T_{@1314nm}$=0.001% and $T_{@1047nm}$=98%). As shown in Fig. 1, the bounce configuration uses a total internal reflection (TIR) at the pump facet of the Nd:YLF, exposing the center of the TEM_{00} mode to the area of highest population inversion.

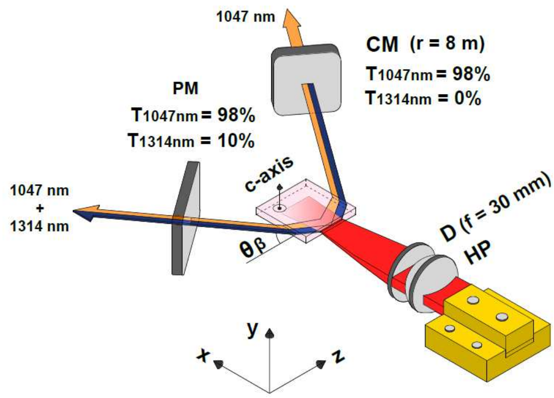

Fig. 1. Single bounce resonator configuration. PM and CM are laser mirrors; D is a doublet with 30 mm focal distance; HP is a half-wave plate.

As the $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition emits both orthogonally polarized wavelength, 1314 nm (σ) and 1321 nm (π), with similar emission cross section (2.4x10^{-20}cm^2 and 2.3x10^{-20}cm^2 respectively) [4], a Brewster angle of 55.4º was employed to reduce the Fresnel losses at the lateral faces of the crystal for the σ wavelength emission. Cavity length was 140 mm. The pump laser was focused by a doublet lens (D), with f = 30 mm. To improve absorption, a half-wave plate (HP) was used set the polarization of the pump to be parallel to the c-axis of the crystal.

The π-transition of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ emitting level has an emission cross section ($\sigma_{e@1047\,nm}$ = 22x10^{-20} cm^2) that is about nine times greater than for the 1314 nm [4]. Oscillation of the

1047 nm emission is achieved by slightly misaligning one of the mirrors in the vertical direction. Hence, this simple and compact laser cavity can selectively emit at 1314 nm, at 1047 nm, or a simultaneously combination of both wavelengths.

III. Results and Discussion

Fig. 2A, B and C shows the spectrum of the laser emitting at 1047 nm, at 1314 nm, and the dual-wavelength regime.

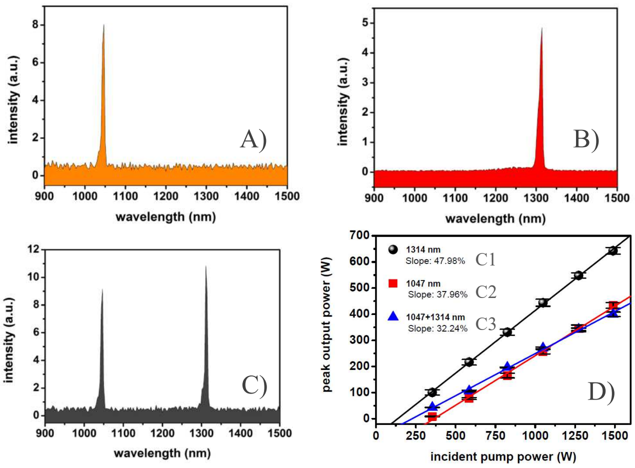

Fig. 2. A: Emission spectrum at 1047 nm, measured by a NIRQuest Spectrometer. B: emission at 1314 nm. C: simultaneous emission of 1314 nm and 1047 nm. D: peak output power curve vs incident power for the Nd:YLF laser. C1: Slope for the 1314 nm emitting laser. C2: Slope of the 1047 nm emitting laser. C3: Curve for the dual-wavelength lasers at 1314+1047 nm.

Fig. 2D shows the peak output power vs the incident pump power after the 3.6% Fresnel losses at the pump face of the crystal. When the laser is aligned to emit at 1314 nm the beam only exits the PM mirror ($T_{@1314nm}$=10%), but when the laser is optimized to operate at 1047 nm or in the dual-wavelength regime, the output emission occurs at both mirrors. The value presented in Fig. 2D represents the sum of the output powers of both mirrors. A slope efficiency of 47.98% and an optical-to-optical efficiency of 43.16% were achieved for the single wavelength emission at 1314 nm. This represents, to the best of our knowledge, the highest optical efficiency attained at 1314 nm to date. As the reflectivity of the PM was optimized to the 1314 nm emission, smaller efficiencies at the 1047 nm were reached. For the single emission at 1047nm a slope efficiency of 37.96% was obtained. Dual-wavelength emission with a near 50/50 split of 1314 nm and 1047 nm presented a slope efficiency of 32.24%. The laser operated with multimode beam quality, presenting a M^2 value of ~8 for the 1314 nm emission. Table 1 presents the complete results for each emission.

TABLE I. Nd:YLF laser results – With Dual-wavelength

Nd:YLF laser	Laser Emission Regime		
	1314 nm	*1047 nm*	*1047+1314nm*
Output Power (W)	643 ± 13	434 ± 11	400 ± 9
Pulse width (μs)	341.9 ± 0.4	315.3 ± 0.6	314 ± 1
Slope efficiency (%)	48.0 ± 0.5	38 ± 1	32.2 ± 0.8
Optical efficiency (%)	43.2 ± 0.9	29.1 ± 0.7	26.8 ± 0.6

IV. Conclusion

Simultaneous emission at 1047 nm and 1314 nm of a side-pumped Nd:YLF laser in a simple and compact cavity is presented. The wavelength selection was made exclusively by cavity alignment and presented a record optical-to-optical efficiency of 43% and a slope efficiency of 48%, when optimized for the 1314 nm emission. Single 1047 nm emission or dual-wavelength emission are also obtained with good efficiencies.

References

[1] N. Pavel, “Simultaneous dual-wavelength emission at 0.90 and 1.06 µm in Nd-doped laser crystals,” *Laser Phys.*, vol. 20, no. 1, pp. 215–221, Jan. 2010.

[2] N. U. Wetter, F. A. Camargo, and E. C. Sousa, “Mode-controlling in a 7.5 cm long, transversally pumped, high power Nd:YVO_4 laser,” *J. Opt. A Pure Appl. Opt.*, vol. 10, no. 10, p. 104012, Oct. 2008.

[3] A. M. Deana, I. M. Ranieri, S. L. Baldochi, and N. U. Wetter, “Compact, diode-side-pumped and Q-switched Nd:$YLiF_4$ laser cavity operating at 1053 nm with diffraction limited beam quality,” *Appl. Phys. B*, vol. 106, no. 4, pp. 877–880, Mar. 2012.

[4] C. Czeranowsky, “Resonatorinterne frequenzverdopplung von diodengepumpten neodym-lasern mit hohen ausgangsleistungen im blauen spektralbereich,” University of Hamburg, 2002.

[5] A. M. Deana, M. A. P. A. Lopez, and N. U. Wetter, “Diode-side-pumped Nd:YLF laser emitting at 1313 nm based on DBMC technology,” *Opt. Lett.*, vol. 38, no. 20, p. 4088, Oct. 2013.

[6] T. de A. Vieira, F. M. Prado, and N. U. Wetter, “Nd:YLF laser at 1053 nm diode side pumped at 863 nm with a near quantum-defect slope efficiency,” *Opt. Laser Technol.*, vol. 149, p. 107818, May 2022.

[7] N. U. Wetter, E. P. Maldonado, and N. D. Vieira, “Enhanced efficiency of a continuous-wave mode-locked Nd:YAG laser by compensation of the thermally induced, polarization-dependent bifocal lens,” *Appl. Opt.*, vol. 32, no. 27, p. 5280, Sep. 1993.

[8] F. M. Prado, T. J. Franco, and N. U. Wetter, “Sub-nanosecond, 41 mJ pulse energy, passively Q-switched Nd:YLF laser,” *Opt. Laser Technol.*, vol. 162, p. 109257, Jul. 2023.

[9] N. U. Wetter and A. M. Deana, “Diode-side-pumped Nd:YLiF 4 laser emitting at 1053 nm with 53.6% optical efficiency and diffraction-limited beam quality,” *Laser Phys. Lett.*, vol. 10, no. 3, p. 035807, Mar. 2013.

[10] B. M. Walsh, “Dual wavelength lasers,” *Laser Phys.*, vol. 20, no. 3, pp. 622–634, Mar. 2010.

[11] Y. F. Chen, Y. S. Chen, and S. W. Tsai, “Diode-pumped Q-switched laser with intracavity sum frequency mixing in periodically poled KTP,” *Appl. Phys. B*, vol. 79, no. 2, pp. 207–210, Jul. 2004.

[12] H. Ahmad, F. D. Muhammad, C. H. Pua, and K. Thambiratnam, “Dual-Wavelength Fiber Lasers for the Optical Generation of Microwave and Terahertz Radiation,” *IEEE J. Sel. Top. Quantum Electron.*, vol. 20, no. 5, pp. 166–173, Sep. 2014.

[13] W. Vollmar, M. G. Knights, G. A. Rines, J. C. Mccarthy, and E. P. Chicklis, “Five-color Nd:YLF laser,” in *Conference on Lasers and Electro-Optics*, Washington, D.C.: OSA, 1983, p. THM2.

[14] F. M. Prado, T. J. Franco, T. de A. Vieira, and N. U. Wetter, “High-power Nd:YLF four-level lasers with 68% slope efficiency,” *Appl. Opt.*, vol. 62, no. 8, pp. C49-C52, Mar. 2023.

[15] F. M. Prado and N. U. Wetter, “Record Optical Efficiency for a Diode-Side-Pumped Nd:YLiF Laser Operating at 1053 nm,” in *2021 SBFoton International Optics and Photonics Conference (SBFoton IOPC)*, IEEE, May 2021, pp. 1–3.

[16] F. M. Prado, T. de A. Vieira, and N. U. Wetter, “68% slope efficiency Nd:YLF laser with 91 W of peak power,” in *Latin America Optics and Photonics (LAOP) Conference 2022*, Washington, D.C.: Optica Publishing Group, 2022, p. Tu4A.47.

[17] F. M. Prado and N. U. Wetter, “Nd:YLF laser pumped at 797 nm with 68% slope efficiency,” in *Solid State Lasers XXXI: Technology and Devices*, SPIE, Mar. 2022, pp. 28-32.

[18] N. U. Wetter and A. M. Deana, “Influence of pump bandwidth on the efficiency of side-pumped, double-beam mode-controlled lasers: establishing a new record for Nd:$YLiF_4$ lasers using VBG,” *Opt. Express*, vol. 23, no. 7, p. 9379, Apr. 2015.

[19] T. de A. Vieira, F. M. Prado, and N. U. Wetter, “Near Quantum Limited Slope Efficiency Nd:YLF_4 Laser,” in *Laser Congress 2021 (ASSL,LAC)*, Washington, D.C.: Optica Publishing Group, 2021, p. AW3A.6.