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Nd:YLF laser at 1053 nm diode side pumped at 863 nm with a near quantum-defect slope efficiency

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ABSTRACT

Laser emission at the 1053 nm transition of Nd:YLF_4 is demonstrated using diode-side-pumping at 863 nm directly into the emitting level. The laser configuration uses one total internal reflection at the pump face and provides the highest slope efficiency reported for the Nd:YLF_4 medium, close to the quantum limit. In quasi-continuous mode, the laser operates with diffraction-limited beam quality and 78.2% slope efficiency with 14.4 W of output power. In continuous mode, 75.7% slope efficiency in both single-mode and multimode operation is achieved, with 13.5 W output power.

1. Introduction

Neodymium (Nd^{3+}) doped laser materials are traditionally pumped into the $^4F_{5/2}$ absorption band at approximately 800 nm, mainly due to its large absorption cross-section when compared to other transitions and its four-level laser nature. Additionally, because of a smaller Stokes shift, in-band pumping (also called thermally boosted pumping or direct pumping) into the upper laser level ($^4I_{9/2} \rightarrow {}^4F_{3/2}$) results in increased slope efficiency as well as less residual heat being produced during the pumping cycle. Due to the smaller absorption cross-section for neodymium in-band pumping, a longitudinal pumping scheme is generally preferred, and this scheme has initially been employed along with several oxide hosts and either Ti:sapphire or diode pumping at around 880 nm [1,2,3]. The highest reported room temperature slope efficiency achieved with the in-band pumping of a neodymium-doped host is, to our knowledge, 82.7%, which was obtained for diode-pumping Nd:YVO_4 at 880 nm [4,5]. The result was achieved for the absorbed pump power, and the absorption efficiency was 55.5%.

Amongst the many types of neodymium-doped crystals, yttrium lithium fluoride ($YLiF_4$) occupies an important position due to its long upper state lifetime (~520 μs), which allows high pulse energies in Q-switched operation, and it has natural birefringence and low temperature variability of its index of refraction, which are both important for high beam quality. In 2010, Lü et al. employed Ti:sapphire to end-pump a Nd:$YLiF_4$ (Nd:YLF) laser and obtained 65.1%, 71.2%, and 76.3% slope efficiencies at 1047 nm for the pump wavelengths of 863 nm, 872 nm, and 880 nm, respectively [6]. Ti:sapphire was also used as the pump source, but with emission at the sigma transition of 1053 nm, Zhang et al. achieved 55% slope efficiency for 872 nm excitation and 63.9% slope efficiency for an 880 nm pump wavelength [7]. Using a fiber-coupled pump diode for end-pumping at 880 nm, Schulz et al. achieved 71% slope efficiency at the 1053 nm laser transition [8]. Recently, in-band pumping at 908 nm has resulted in 73.9% slope efficiency at 1053 nm [9].

In-band-pumping is generally associated with small absorption efficiency due to the very small absorption cross-sections at the pumping wavelengths, decreasing the overall efficiency of a laser system and hampering its usefulness. Typical absorption efficiencies for Nd:YLF for incident pump power in longitudinal pumping schemes are up to 100% at 863 nm, 65% at 872 nm, 52% at 880 nm, and 4.5% at 908 nm [8,10]. As shown in Fig. 1, the highest absorption peak for direct-pumping of the $^4F_{3/2}$ energy level occurs at 863 nm, and this peak is roughly half the height of the absorption peak at 797 nm belonging to the $^4F_{5/2}$ transition. It is a special characteristic of neodymium-doped birefringent crystals such as Nd:YVO_4, Nd:$GdVO_4$, and Nd:YLF that they present such high absorption peaks for the $^4F_{3/2}$ absorption band. However, for vanadate crystals, this peak is located at longer wavelengths around 880 nm. For Nd:YLF, this translates into a still considerable absorption coefficient (Fig. 1) of $\alpha = 5.3\ cm^{-1}$ at 1% neodymium doping when compared to the other three-level pump transitions at 872 nm, 880 nm, and 908 nm, which show measured absorption coefficients of $1.2\ cm^{-1}$, $0.9\ cm^{-1}$ and $0.1\ cm^{-1}$, respectively. A smaller absorption coefficient requires a longer spatial overlap between a pump and a laser beam to achieve good energy efficiency, which is harder to achieve in a side-

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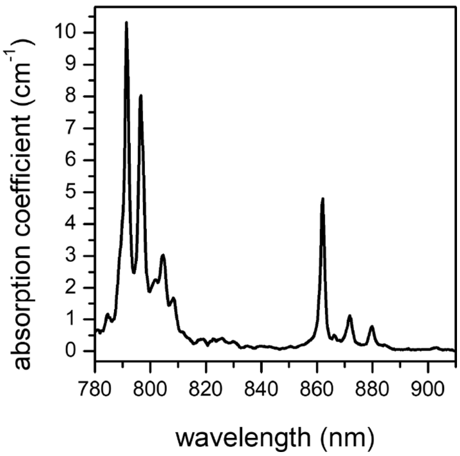

Fig. 1. Measured π-polarized absorption spectra of the 1 mol% doped Nd:YLF crystal (0.2 nm spectrometer resolution).

pumped setup. Therefore, to maintain good overall efficiency with side-pumping, the 863 nm pump wavelength is the best choice.

One possibility for in-band side-pumping is to use a multi-pass resonator for which the fundamental beam undergoes several passes through the gain sheet. Pati et al. reported a multimode output beam with a slope efficiency of 60% at 1047 nm for side-pumping at 863 nm using two opposing diodes and five passes through the region of pump induced inversion [10].

Another efficient and successful configuration employing side-pumping is bounce geometry [11]. As shown in Fig. 2, the bounce configuration uses total internal reflection (TIR) at the pump face, thereby exposing the center of the TEM_{00} mode directly to the region of highest population inversion, resulting in excellent laser efficiency. In this configuration, a large laser mode in the pump direction is essential to achieve good spatial overlap with the pump inversion (gain sheet), which may be achieved by using cylindrical intracavity lenses in a plane-plane resonator configuration. Many researchers have used this resonator configuration to achieve good efficiency, especially in connection with the $Nd:YVO_4$ gain material due to its very high absorption coefficient [12]. Given the lower absorption cross-section of Nd:YLF, we do not use a grazing incidence angle at the pump face, but rather an angle of 55.4° [13].

An alternative solution to cylindrical lenses can be achieved by using a three-mirror resonator, generating two passes through the laser crystal and two TIRs at the pump face inside the pump region instead of one. In this case, the second beam is laterally offset within the gain sheet to create a better overall spatial overlap between the gain and the laser beam [13,14]. This technique has been dubbed double-beam mode-controlling (DBMC), and it has generated the highest slope efficiencies so far for pumping Nd:YLF at the traditional pumping wavelengths around 800 nm ($^4F_{5/2}$ level). These slope efficiencies are higher than the efficiencies for end-pumping with Ti:sapphire (slope efficiency of 55.6%) [6]. Using 792 nm diode side-pumping, a slope efficiency of 63.5% and an optical efficiency of 53.6% with diffraction-limited beam quality were demonstrated at 1053 nm [15].

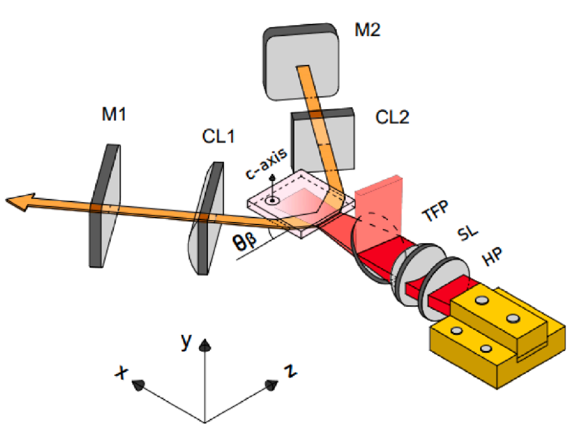

Fig. 2. Bounce configuration. M1 is a plane output coupling mirror and M2 is a flat high reflector. CL1 and CL2 are cylindrical lenses with focal lengths of 100 mm. Θ_B is the Brewster incidence angle of the laser beam. TFP: thin-film polarizer; SL: spherical lens; HP: half-wave plate.

Apart from the optimization of the spatial overlap between pump inversion and a laser beam, further refinement is also mandatory for high efficiency during side-pumping, which is a good spectral overlap. If the diode's emission is larger than the width of the crystal's absorption peak, part of the pump energy spectrum will be absorbed deeper inside the crystal and will not coincide with the laser beam crossing the crystal at the pump surface, causing an efficiency loss. Using a volume Bragg grating (VBG)-equipped diode to narrow down the diode's emission linewidth (0.5 nm FWHM) at 797 nm, a slope efficiency of 65% and an optical efficiency of 60% have been demonstrated at the laser emission wavelength of 1053 nm [16].

In this work, we report laser emission in Nd:YLF at the 1053 nm transition for pumping directly into the $^4F_{3/2}$ upper laser level at 863 nm. The obtained slope efficiencies of 78.2% in quasi-continuous wave (QCW) single-mode (near the quantum limit of 81.9%) and 75.7% in continuous wave (CW) multimode are, to our knowledge, the highest reported so far for Nd:YLF lasers operated at any pump wavelength. The QCW mode of operation is especially attractive for passive Q-switching because the timing jitter and the pulse-to-pulse power instability can be orders of magnitude smaller than those during CW passive Q-switching, combining some of the benefits of active Q-switching with the simplicity and compactness of passive Q-switching [17].

2. Experimental setup

For the experimental configuration, an a-cut Nd:YLF crystal with dimensions of 13 mm × 13 mm × 1.5 mm with 1 mol% dopant and a c-axis oriented perpendicular to the larger slab faces was employed. The gain medium was placed in a symmetric resonator with a length of 343 mm with two flat mirrors, one highly reflecting (M2) at 1053 nm and one output coupler (M1) with 10% transmission, as shown in Fig. 2. The larger top and bottom surfaces (13 mm × 13 mm) were in contact with a water-cooled copper heat sink. The fast-axis collimated pump diode (DILAS, model M10Y; 1 cm wide diode-array with a 50% filling fraction and without a VBG) had its peak emission at 863 nm and required an anti-reflection coated half-wave plate (HP) to rotate the polarization of the pump beam to coincide with the crystal's highly absorbing π-polarization along the vertical direction. The diode was focused by a spherical lens (SL) with f = 40 mm, resulting in a spot size at the crystal's pump face with dimensions of 4.5 mm and 130 μm along the horizontal and vertical directions, respectively.

A thin-film polarizer (TFP) was placed at 45° incidence (with respect to the y-axis) behind the spherical lens to reflect any TE polarization. The total transmission of the complete focusing system was 92 ± 1%, including a 3.6% transmission loss (index of refraction $n_e = 1.47$) at the crystal's uncoated pump facet. The laser diode was always operated in continuous mode at maximum pump power, and the maximum absorbed power of the crystal was 21.6 W. Control of the absorbed power was obtained by varying the angle of the half-wave plate (0-40°) in conjunction with the TFP. A calibration curve can be seen in Fig. 3 that shows the total power absorbed by the crystal that was obtained by measuring the pump power directly in front of the crystal's input face and subtracting an additional 3.6% due to the uncoated pump facet. Two intracavity, AR-coated (0.03% loss per surface) cylindrical lenses with a focal distance of $f_y = 100$ mm were placed 85 mm from the slab's facets, resulting in a beam inside the crystal with dimensions of 280 μm

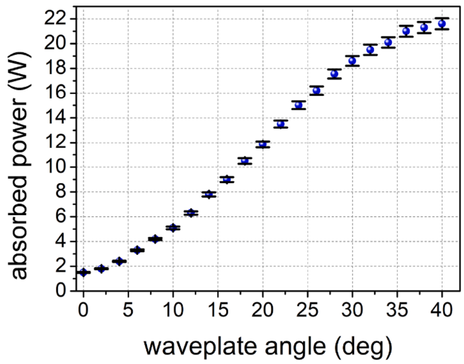

Fig. 3. Absorbed pump power as a function of half-wave plate tuning angle.

(simulated using LASCAD software) in the vertical direction and 4.5 mm in the horizontal direction, as calculated from the measurements of the beam profile immediately behind the output coupler (Fig. 2). For good efficiency, all of the pump energy had to be absorbed within the width of the laser beam inside the crystal, which was 5.5 mm in the x-direction, given the incidence angle of 55.4° at the pump surface. The diode emission had a measured FWHM of 1.1 nm at 863 nm and maximum CW pump power, whereas the crystal's absorption peak had a measured FWHM of 1.9 nm (measured with an instrument supplied resolution of 0.2 nm, Agilent Inc., model CARY 5000). Therefore, the entirety of the spectra of the diode's pump radiation was absorbed with an effective absorption coefficient of $\alpha = 4.7\ cm^{-1}$.

3. Results and discussions

Quasi-CW mode operation was obtained using a chopper to modulate the diode's emission, producing a low duty cycle of 3.2% with a 650 ± 10 μs (FWHM) pump pulse duration. In this mode, a laser peak output power of 14.4 ± 0.3 W was measured for an absorbed pump power of 21.60 ± 0.45 W, resulting in 66.7 ± 1.6% optical-to-optical efficiency and 78.2 ± 0.9% slope efficiency (Fig. 4). This result is given as a function of the absorbed pump power in Fig. 4a for comparison purposes with other results from the literature that might have presented low absorption efficiencies. When calculating with respect to the average power, the slope efficiency was 66.5 ± 1.1%. When considering the incident pump power, a slope efficiency of 75.4 ± 0.9% as a function of the incident pump power was obtained because the only losses originated from the uncoated pump face (Fig. 4b).

The result represented a 15% increase when compared to an earlier result in the literature (for Nd:YLF) with respect to the incident pump power (65.1%, Ti:sapphire pump at 863 nm; [6]). As seen in Fig. 4c, the laser emission at 1053 nm had a pulse duration of 550 ± 10 μs (FWHM) at the maximum pump power. The inset of Fig. 4c shows the pump and the laser pulse at maximum pump power. All of the power measurements were performed using two different, calibrated power meters (model PM10V1 from COHERENT and the model S322C from Thorlabs), giving identical results. The output beam had an elliptical shape with the quality factors M^2 of 1.08 and 1.09 in the horizontal and vertical directions (beam profiler NEWPORT, model LBP), respectively, as shown in Fig. 5.

Without the chopper, a CW output power of 13.50 ± 0.27 W was obtained with 75.7 ± 1.2% slope efficiency and 63.0 ± 1.8% optical efficiency. As seen in Fig. 4a, the slope efficiency remained approximately the same upon changing from QCW to CW. The output beam quality was always monomode in the vertical direction ($M^2 < 1.5$), whereas the horizontal beam quality changed from initially monomode (up to ~ 1.8 W of the output power) to increasingly multimode. A dominant TEM_{50} was observed at the highest output power, corresponding to an M^2 of approximately 11. No roll-over was observed up to the highest CW pump power, demonstrating the absence of deleterious thermal effects.

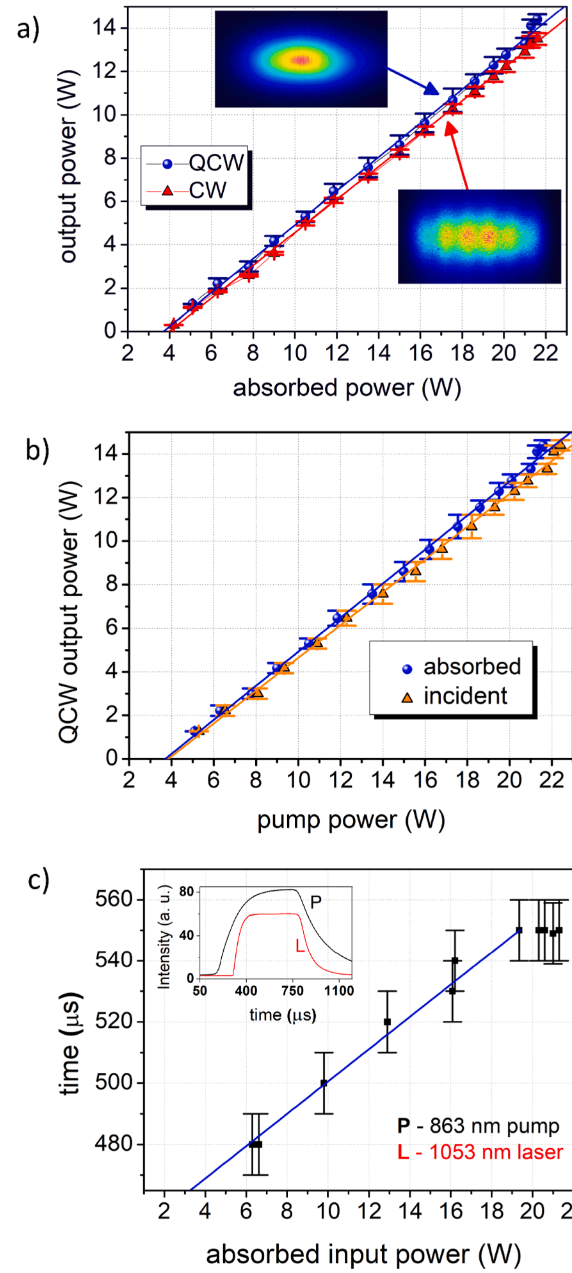

Fig. 4. a) Peak output power versus absorbed diode pump power for quasi-continuous (QCW) and continuous (CW) mode. The linear fit presented residuals STDs of 0.2 W and 0.15 W for the QCW mode and the CW mode, respectively. The inset shows a picture of the output beam for CW or QCW operation. b) Comparison of QCW output power as a function of the absorbed and incident pump power. The fitted curves both present a residual STD of 0.2 W with respect to the incident power. c) Laser pulse duration at FWHM versus absorbed input power. Linear regression with a residual STD of 3 μs was the best fit for the experimental points up to 19.3 W of the input power. For higher input powers, the pulse duration remained constant (550 μs) up to the maximum input power of 21.6 W. The inset shows the oscilloscope traces of the laser pulse (L) and the pump pulse (P), in arbitrary units, measured with a Si photodiode.

During CW operation, the thermal gradient in a crystal increases, and as a consequence, a small, negative thermal lens is introduced due to a negative dn/dT along the σ-polarization direction (x-axis), whereas a positive contribution comes from the end-face bulging at the pump facet. The introduction of intracavity cylindrical lenses reduces the dimension

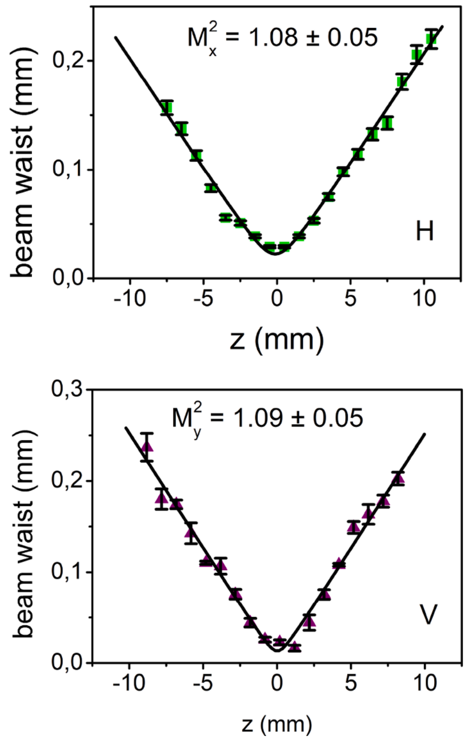

Fig. 5. Measurement of beam quality for QCW mode. *V*: vertical M^2; *H:* horizontal M^2. The fitted curves present residual STDs of 10.7 µm and 7.2 µm for the vertical and horizontal directions, respectively.

of the beam along the y-axis in the thermal lens region, decreasing the effects of pump-face bulging along the vertical direction. However, along the x-axis, pump-face bulging acts like a focusing lens on the large intracavity beam size, which is generated by the flat–flat resonator configuration, decreasing the beam's width and allowing higher-order transverse modes to oscillate in the cavity.

A way to overcome the occurrence of multimode during CW operation would be the use of the DBMC configuration, which is described in the introductory section. The DBMC configuration enforces single lateral mode operation. Because DBMC uses two separate passes through the gain sheet inside a crystal and a concave folding mirror with a relatively short radius (150 mm), as opposed to the two plane mirrors in the presently used configuration, there is less influence of thermal lensing on the mode profile, causing single-mode operation even with high CW pump powers [18].

We employed a thin crystal (1.5 mm) for better refrigeration, which allowed us to achieve higher CW output powers for high pump intensities even though Nd:YLF has a fracture limit that is five times smaller (40 MPa) than that of Nd:YAG. It has already been shown that a 1 mm thick Nd:YLF crystal can be pumped with > 200 W of CW pump power at 806 nm [19], thereby taking full advantage of the crystal's crystalline qualities and long upper state lifetime, which allows for very high energy Q-switched pulses at almost diffraction-limited beam quality. A drawback of a thinner crystal is that it does not allow the DBMC configuration, because when DBMC is used, the ratio of the beam height to the beam width is given by the crystal's index of refraction due to the Brewster incidence of the beam at the slab's side facets (see Fig. 2). As a result, the intracavity beam is much larger in the y-direction than in the current configuration, and a thicker crystal (~3 mm) would be needed, which would limit the maximum CW pump power.

The comparison with other neodymium-doped laser crystals using incident pump power instead of absorbed pump power is important because it is directly related to the total electrical efficiency of the system. When considering this more useful definition of slope efficiency, the result of 75.4 ± 0.9% (QCW) obtained with our setup using Nd:YLF_4 is, to our knowledge, the highest achieved for diode pumping of any neodymium-doped host at room temperature, except for one recent work that achieved a higher slope because of the absence of temperature tuning at low pump powers [20].

4. Conclusion

We report laser emission in Nd:YLF at the 1053 nm transition for diode pumping directly into the $^4F_{3/2}$ upper laser level at 863 nm. In QCW operation, the laser was always operated with near-diffraction-limited beam quality with a peak output power of 14.4 W. The slope efficiency was 78.2% in QCW single-mode operation and 75.7% during CW (single-mode and multimode) operation.

The setup also represents a solution to the low fracture limit of Nd:YLF by employing a thin crystal, a technique that has already demonstrated feasibility for CW pump powers beyond 200 W.

The presented Nd:YLF laser resonator takes full advantage of the crystal's known qualities, such as low thermal birefringence and a long upper state lifetime, while also demonstrating record efficiency even when compared to other neodymium-doped hosts.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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