Double-beam-mode-controlling diode-side-pumped Nd:YLF laser with near 60% efficiency

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ABSTRACT

The double-beam, mode-controlling technique (DBMC) is a compact side-pumped laser design, very advantageous for systems based on active media with intermediate absorption cross section, such as Nd:YLiF$_4$ (Nd:YLF). Recently, a record optical efficiency of 53.6% and 63.5% slope efficiency has been achieved for a Nd:YLF laser emitting at 1053 nm with diffraction limited beam quality. In this work we review our results using the DBMC design and present the latest achievements exploiting new ways to push the limit of this technique to higher pump powers. By narrowing down the laser emission bandwidth of the pump diode bar using a volume Bragg gratings (VBG) we increased the effective absorption cross section in the Nd:YLF crystal, improving the spatial overlap between pump and laser beam. With this setup the laser delivers 68 W peak fundamental mode output power at 115 W of QCW absorbed peak power, resulting near 60% of optical-to-optical efficiency which is, to the best of our knowledge, the highest efficiency ever reported for a Nd:YLF laser, considering even longitudinal pump schemes. The results reported here highlight the remarkable advantages of the side pumped DBMC laser scheme versus longitudinal pumped laser set-ups, showing that the efficiency of the side-pumped DBMC laser is not suppressed by its spatially weaker overlap between pump and laser mode and preserving single mode laser operation, even at high pump powers.

Keywords: Lasers, Nd:YLF, record efficiency, DBMC, solid state lasers, diode side pumping

1. INTRODUCTION

The first diode-pumped laser was invented only four years after the Maiman's famous ruby laser [1,2]. And although high-efficiency has been always associated to diode-end-pumping, the first design was a GaAs diode-side-pumped U^{3+}:CaF$_2$ rod laser. In this set-up, the pump beam is perpendicular to the laser beam and therefore, the overlap efficiency between pump and laser beam and the pump intensity is usually lower in comparison to end-pumped schemes. This is because the highest pump inversion is generated at the lateral surface of the rod where the pump beam enters the active medium and therefore does not coincide with the highest intensity of the laser mode. Additionally, this may cause multimode operation of the laser system which is another concern for side-pumped lasers.

The motivation to use side-pumping is manifold: Asides from the lack of power scalability in traditional end-pumped designs and their need for expensive pump diodes that incorporate beam shaping or fiber coupling, side-pumped designs involve generally less components and are much more compact and therefore robust. One successful approach to mitigate the efficiency problem and the occurrence of multimode operation during side-pumping was accomplished by Minassian [3]. In his design, an active medium with high absorption coefficient was used to limit the penetration depth of the pump, confining it to a region close to the pump surface. Additionally the laser is aligned in a grazing incidence, undergoing a total internal reflection (TIR, also called "bounce" by the authors) at the pump surface instead of making the laser just pass through the crystal, thereby efficiently screening the inverted population and achieving near quantum efficiency [3].

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In order to maintain the laser oscillating in fundamental mode, this grazing incidence requires the usage of cylindrical lenses inside the resonator to produce highly elliptical beams instead of circular ones. In addition, such an approach can only be used for materials of very high absorption coefficient such as $Nd:YVO_4$ ($\alpha > 60$ cm^{-1} at 808 nm) or, otherwise, multimode operation occurs. Less absorbing crystals require a new technology or inevitably result in higher order mode oscillation along with lower efficiency [4].

In 2008 Souza *et al* and Wetter *et al* presented a different approach [4,5]. In their design (later known as Double Beam Mode Controlling - DBMC), a square Nd:YLF laser (with low absorption coefficient in comparison to $Nd:YVO_4$) was side-pumped by a laser diode. To efficiently screen the pump power in deeper regions of the crystal, the laser beam makes a TIR at the pump facet at a smaller incidence angle and is not grazing. In addition, simulation and experiment demonstrated that the crystal could be of square shape using Brewster's angle at the crystal entrance and exit facets avoiding the usage of coatings at all surfaces of the active medium. This not only decreases the overall cost of the system but also allows using all four sides of the square crystal in the case that surface damage should occur. Additionally, different laser lines may be operated within a single crystal (1321 nm and 1053 nm), as demonstrated by Deana *et al* in ref [6].

One important issue with side-pumped lasers is beam quality. Even at low pump powers higher order modes start to oscillate. The classical solution is to introduce a hard aperture inside the resonator, but this considerably decreases the overall efficiency. The solution proposed by the authors was to introduce a third folding mirror that slightly displaces the laser inside de resonator resulting in a second TIR at the pump facet, near parallel to the first one and only displaced by about a millimeter [5]. The displacement is such that the two beams do only overlap for higher order modes but not for the fundamental mode. This effectively creates a soft aperture which gives preference to operation in fundamental mode.

By using a Nd:YLF crystal with 1 mol% of neodymium doping, this laser has achieved a slope efficiency of 63.5%. At 35.4 W of absorbed power, the laser delivered 19 W peak power with beam quality of $M^2 = 1.31$, resulting in an optical-to-optical efficiency of 53.6% which was the highest efficiency ever reported for pumping into the $^4F_{5/2}$-band (800 nm band) and emitting at the $^4F_{3/2} \rightarrow {^4I_{11/2}}$ $Nd:YLF_4$ main laser transition, considering both polarizations (π and σ) and even end-pumped designs which, compared to side-pumped schemes, should show better overlap between pump beam and fundamental mode of oscillation [7].

For strongly absorbing crystals such as $Nd:YVO_4$, DBMC can be very interesting because it avoids the usage of cylindrical intracavity lenses necessary to create the highly elliptical beams used in bounce resonators [3]. Using a DBMC - Nd:YVO laser in a compact, 7.5 cm long cavity, 22 W of cw output power in fundamental mode at 74% slope efficiency have been achieved [8, 9].

Besides quasi-continuous wave operation this design was also tested during Q-switching conditions [10, 11]. By using a Cr:YAG crystal as passive Q-switch in a Nd:YLF DBMC laser, up to 3.2 mJ of energy per pulse at 12 ns pulse duration and 500 Hz repetition rate were achieved [12,13]. High repetition rates (up to KHz-level) were also shown [10, 11], demonstrating therefore the versatility of this design.

Power scalability is another main issue for optical engineers. Usually this may be done either by a master oscillator power amplifier (MOPA), in which a second active medium is placed outside the master oscillator, or by placing additional crystals inside the same resonator. By using a folding mirror of long radius of curvature (10 m) within the DBMC approach, the laser beam presents a diameter of approximately 1.1 mm throughout the whole resonator, allowing for a resonator of several meters in length with spare place for additional gain media, while still maintaining fundamental mode of oscillation and high efficiency. Simulation showed that placing the second laser crystal inside the resonator results in 57 % amplification of the laser power, which was confirmed by the experiment, whereas an optimized single pass MOPA amplifier, using the same beam diameter and pump beam power, would result in only 36 % of amplification [14]. Besides, the former approach requires no additional optics. The same simulation demonstrated that at least five passes through the amplifier of the MOPA configuration would be necessary, at the same beam diameter and pump power, to achieve similar results as in a DBMC laser with two crystals inside the same cavity.

This clearly demonstrates how easy power scalability can be achieved with the DBMC design. In practice, the large number of air/crystal interfaces increases alignment difficulties and the overall losses of the resonator. With two crystals inside the resonator, the DBMC resonator presented 7.5 % losses that were attributed to the sixteen air/crystal interfaces and eight total internal reflections at the pump facets that the beam undergoes during each round-trip. The average loss per interface was 0.3%. An optical-to-optical efficiency of 42 % and slope efficiency of 46 % were demonstrate by the laser while still maintaining fundamental mode of oscillation even at 110 W of total absorbed pump power [14].

The ongoing research and simulations of the design has demonstrated that higher efficiencies are possible by improving the spatial overlap between the pump source and the fundamental mode of oscillation of the resonator. This can be achieved by decreasing the penetration depth of the pump beam, favoring high population inversion closer to the pump surface at which the laser beam makes the TIR, optimizing thereby spatial overlap and increasing the overall efficiency.

Decreasing the penetration depth may be achieved by increasing the doping concentration of the neodymium in the YLF host beyond 1% (of our current crystal) but that would also increase crystalline defects and overall losses. Similar results can be achieved by employing a different approach: optimization of the spectral features of the pump diode.

In this work we present the latest developments on the DBMC technology, achieving higher efficiencies and output powers for Nd:YLF lasers using spectral pump narrowing.

2. THEORY AND SIMULATIONS

Figure 1 shows the schematic diagram of the DBCM laser. The intracavity beam undergoes a TIR at the pump facet, gets reflected by folding mirror M2 and then undergoes a second TIR. The separation between both beams is approximately 1 mm and the internal angle of incidence at the pump facet is 56.4 degrees.

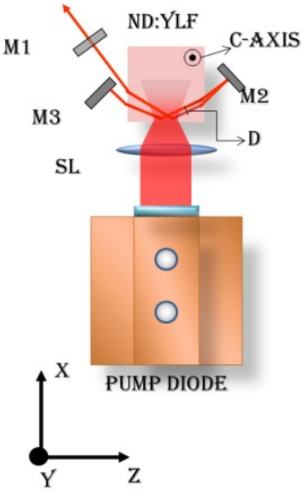

Figure 1. Schematic diagram of the DBMC laser. The a-cut 1 mol% Nd:YLF crystal (Crystech) has dimensions of 13 mm x 13 mm x 3 mm and the c-axis is orientated perpendicular to the large cooling facets. All surfaces are polished and uncoated. The resonator has two highly reflecting mirrors, one flat (M2) and one curved folding mirror (M3) with 3 m radius of curvature (ROC). The transmission of the flat output coupling mirror (M1) is 20%. SL is a spherical focusing lens.

Figure 2 is a photo taken of the two beams undergoing TIR at the pump surface (dark lines). The bright spot at the pump surface is caused by up-conversion of the only partially depleted inversion.

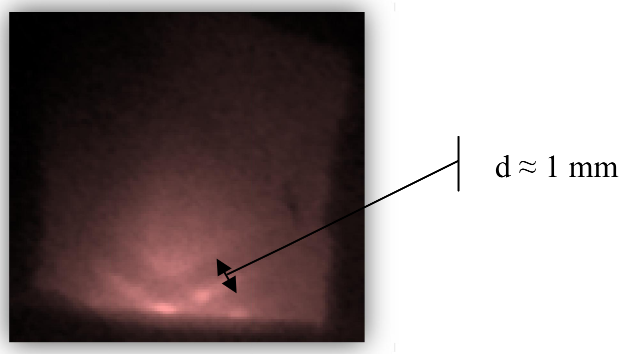

Figure 2. Photo of the upconversion luminescence observed in a Nd:YLF - DBMC laser. The two beams undergoing total internal reflection at the pump surface can be observed.

The incomplete depletion causes a series of unwanted effects such as efficiency decrease and heating and must therefore be avoided. We have measured 35% of up-conversion in non-lasing Nd:YLF with a set-up similar to the one used in [15], demonstrating that this effect is much more pronounced in Nd;YLF than in other materials [16].

It has been shown that in such a resonator, the threshold of the fundamental mode is always smaller than the threshold of the next higher order mode [17], which is explained by the fact that the TEM_{00} mode has a higher power density at its center, when compared with other modes and therefore, also receives the highest pump inversion upon TIR, when the center is exposed directly at the pump surface. This situation is therefore quite different from traditional side-pumping, where the intracavity beam travels parallel to the pump surface inside the crystal resulting in equal probability of oscillation for all transversal modes (apart from diffraction losses), as shown in [6].

Even if the laser starts to oscillate at threshold in the fundamental mode, there is still the possibility that it may change to multimode soon after the threshold. It is therefore important that the soft-aperture effect, that prevents multimode operation as explained in the introduction, should allow for as high pump powers as possible before multimode oscillation occurs. The theory that explains at which threshold pump power multimode operation occurs is given in [9, 17]. Simply put, the theory demonstrates that for a given DBMC set-up this threshold depends only on the product of absorption coefficient times beam waist in the horizontal direction, whereby the absorption coefficient is the effective absorption coefficient, defined as overlap integral between pump diode emission spectra and absorption cross-section spectra of the crystal.

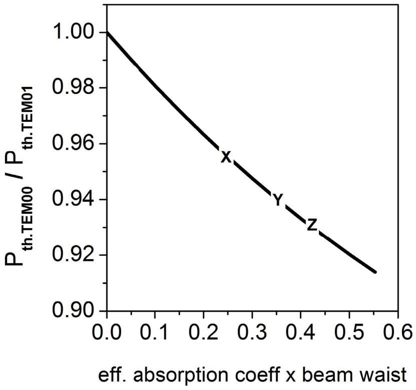

Figure 3. Simulation of the discrimination at threshold against TEM_{01} higher order mode in a DBMC resonator that has the same characteristics as in [7]. X: resonator pumped by a 3 nm wide 797 nm diode; Y: resonator pumped by a VBG equipped diode; Z: resonator pumped by a VBG equipped diode and with a 10 m ROC folding mirror causing a beam waist of 0.6 mm outside the crystal.

As shown in the experiment section, the peak absorption coefficient of our Nd:YLF crystal is 8 cm^{-1}, however, when using a diode of 3 nm (FWHM) spectral width the effective absorption coefficient drops to 4 cm^{-1}. A VBG equipped diode of 0.5 nm width has a much better effective absorption coefficient of 7 cm^{-1} [18]. In figure 3 these results are shown for the cavity described in [7], with a intracavity beam waist of 0.5 mm (X and Y in figure 3) and a beam waist of 0.6 mm (Z). The simulation is based on a MTALAB code similar to the one described in detail in ref. [19].

3. EXPERIMENT

The set-up used in our experiments is shown in Figure 1. The duty cycle was kept at 5% to avoid thermal fracture. The pulse pump pulse duration was 350 µs. Figure 4 shows the spectrum of the Nd:YLF crystal used in this experiment.

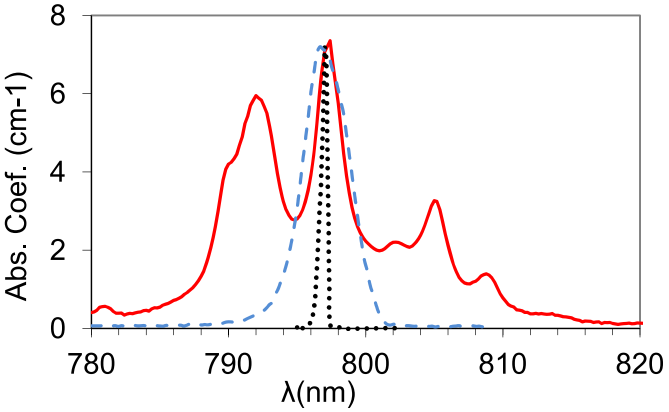

Figure 4. (Color available in the online version) The solid red line represents the π-polarization absorption spectrum of the 1 mol% Nd:YLF crystal used in this experiment. The dashed blue line represents the emission spectrum of the pump diode source used in this work. The custom VBG equipped 797 nm diode (dotted black line) has a bandwidth of only 0.5 nm. Also shown for comparison is a typical 797 nm diode (without VGB), which has a bandwidth of 3nm (solid line).

The 792 nm transition shows less absorption when compared with 797 nm. However, if a regular diode with approximately 2-3 nm spectral bandwidth (FWHM) is employed as pump source, the wider bandwidth of the 792 nm absorption line matches the broad emission of the diode better, resulting in higher efficiencies, as demonstrated in ref. [6]. The higher (and narrower) 797 nm absorption peak is only advantageous when the pump diode has a narrower spectral bandwidth, as shown in ref. [18]. A diode equipped with volume Bragg grating (VBG), which has a bandwidth of only 0.5 nm, should therefore fare better.

In this work we employed a custom made diode coupled to a VBG (Northrop Grumman, USA) right after the fast axis collimating lens in order to tune the spectral peak to 797.0 nm and narrow the bandwidth to 0.5 nm FWHM, as shown in Figure 4. The diode beam was focused into the crystal by a f = 20 mm spherical lenses, resulting in spot size of approximately 4 mm width and 0.1 mm height. After the focusing optics and Fresnel reflections at the uncoated pump facets, about 88.5% of the pump power was effectively absorbed by the slab, resulting in a maximum absorbed pump power of 115 W. The intracavity beam had a beam waist of 0.5 mm outside the crystal.

4. RESULTS AND DISCUSSIONS

With this setup, the laser threshold was 8 W of pump power and the maximum power fluctuation, after a few minutes of warm-up time, was less than 2% over a test period of 4 h. The slope efficiency of the laser was 65% and the losses were 1.4%. At the maximum available absorbed pump power of 115 W, the output power was 68.7W, with diffraction limited beam quality.

Higher transversal modes oscillations are avoided by the soft aperture created by the DBMC technique, resulting in an excellent beam quality of M^2 values of 1.01 and 1.34 in the vertical and horizontal direction, respectively, at the highest available pump power [18]. However, simulations show that at higher pump powers (>115 W) the soft aperture cannot avoid the oscillation of higher order transversal modes anymore. In such a case the effective absorption coefficient or the beam waist should be increased. The maximum pump power at which this soft aperture can still avoid the oscillation of higher order transversal modes may be further increased by adding a forth mirror, which will result in a third bounce at the pump facet and compete with the already existing two near-parallel beams inside de resonator over gain, increasing the threshold for higher order transversal modes.

In comparison with the previous result in [7], with this optimization we obtained an even higher optical-to-optical efficiency of 59.8 %.

5. CONCLUSIONS

In conclusion, these results highlight the some distinctive features of the DBMC laser scheme which help to understand why the efficiency of this side-pumped laser is not suppressed and good mode overlap between pump beam and laser beam is still preserved even in single mode laser operation.

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REFERENCES

[1] Keys, R. J., "Injection luminescent pumping of CaF2:U3+ with GaAs diode lasers, " Appl. Phys. Lett. 4, 50 (1964)
[2] Maiman, T.H., "Stimulated optical radiation in ruby, " *Nature* **187,** 493-494 (1960)
[3] Minassian, A., Thompson, B. and Damzen, M. J., "Ultrahigh-efficiency TEM_{00} diode-side-pumped Nd:YVO_4 laser, " Appl. Phys. B 76, 341–343 (2003)
[4] Wetter, N. U., Sousa, E. C., Camargo, F. A., Ranieri, I. M and Baldochi, S. L., "Efficient and compact diode-side-pumped Nd:YLF laser operating at 1053 nm with high beam quality, " J. Opt. A: Pure Appl. Opt. 10, 104013 (2008).
[5] Souza, E. C., Ranieri, I. M., Baldochi, S. L. and Wetter, N. U., "Compact diode-side-pumped Nd:YLF laser with high beam quality, " AIP Conference Proceedings 992, 426-430 (2008).
[6] Deana, A. M., Lopez , M. A. P. A. and Wetter, N. U., "Diode-side-pumped Nd:YLF laser emitting at 1313 nm based on DBMC technology, " Opt. Lett. 38, 4088 - 91 (2013).
[7] Wetter, N. U. and Deana, A. M., "Diode-side-pumped Nd:$YLiF_4$ laser emitting at 1053 nm with 53.6% optical efficiency and diffraction-limited beam quality, " Laser Phys. Lett. 10, 035807 (2013)
[8] Wetter, N.U., Camargo, F.A. and Sousa, E.C., "Mode-controlling in a 7.5 cm long, transversally pumped, high power Nd:YVO laser," J. Opt. A Pure Appl. Opt. 10(10), 104012 (2008)
[9] Camargo, F. A. and Wetter, N. U., "High power, good beam quality Nd:YVO_4 laser using a resonator with high extinction ratio for higher-order mode Thresholds,"AIP Conference Proceedings 992, 420-425 (2008).

[10] Deana, A. M., Sousa, E. C., Ranieri, I. M., Baldochi, S. L. and Wetter, N. U., "1kHz repetition rate, mode-controlled, passively Q-switched Nd:YLF laser operating at 1053 nm," Proc. SPIE 8235 82350G (2012).

[11] Deana, A. M., Ranieri, I. M., Baldochi, S. L. and Wetter, N. U., "Compact, diode-side-pumped and Q-switched Nd:YLiF$_4$ laser cavity operating at 1053 nm with diffraction limited beam quality, " Appl. Phys. B. Las. and Opt. 106, 877-80 (2012).

[12] Deana, A. M. and Wetter, N. U., “High-efficiency, Q-switched and diffraction-limited Nd:YLF side pumped laser, ” Proc. of SPIE Vol. 8433 84330B (2012)

[13] Wetter, N. U, Ferrari, M., Sousa, E. C., Ranieri, I. M. and Baldochi, S. L., "Q-switching of a mode-controlled, diode-side-pumped Nd^{3+}:YLiF$_4$ laser at 1053 nm with high efficiency and diffraction limited beam quality, " in Advances in Optical Materials, OSA Technical Digest (CD) (Optical Society of America, 2011), paper ATuB22 (2011)

[14] Wetter, N. U. and Deana, A. M., “Power scaling of a side-pumped Nd:YLF laser based on DBMC technology,” Appl. Phys. B Opt. and Las. 117(3), 855-860 (2014).

[15] Jakutis, J., Gomes, L. C., Amancio, C.T., Kassab, L.R.P., Martinelli, J.R. and Wetter, N.U., ”Increased Er3+ upconversion in tellurite fibers and glasses by co-doping with Yb3+,”Opt. Mat. 33, 107–111 (2010)

[16] Courrol, L. C., S. de Lima, B. L., P. Kassab, L. R., Del Cacho, V. D., Tatumi, S. N., Gomes, L. R., Wetter, N. U. "Up-conversion losses in Nd3+ doped lead fluoroborate glasses," J. Non-Cryst. Solids 348, 98-102 (2004)

[17] Wetter, N. U., Sousa, E. C., Ranieri, I. M. and Baldochi, S. L., "Compact, diode-side-pumped Nd3+:YLiF4 laser at 1053 nm with 45% efficiency and diffraction-limited quality by mode controlling, " Opt. Lett. 34, 292 (2009).

[18] Wetter, N. U. and Deana, A.M., “Influence of pump bandwidth on the efficiency of side-pumped DBMC lasers: establishing a new record for Nd:YLiF4 lasers using VBG”, in press.

[19] Matos, P. S. F., Wetter, N. U., Gomes, L., Ranieri, I. M. and Baldochi, S. L., "A high power 2.3 µm Yb:Tm:YLF laser diode-pumped simultaneously at 685 and 960 nm, " J. Opt. A: Pure Appl. Opt. 10, 104009 (2008)