Record Optical Efficiency for a Diode-Side-Pumped $Nd{:}YLiF_4$ Laser Operating at 1053 nm

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***Abstract*—Here we compare the efficiency and beam parameters of different single-bounce $Nd{:}YLF_4$ resonators. A total of five cavities were made by changing both, the curved mirror and the output coupler of the resonator. The best configuration resulted in a cavity that generated a record optical-to-optical efficiency of 63.3% and 66.4% of slope efficiency, with a peak output power of 64.5 W for a pumping power of 101.8 W at 797 nm.**

Keywords— Lasers, neodymium, diode-pumped, $Nd{:}YLF_4$, solid-state lasers

I. Introduction

The efficiency of diode-pumped solid-state lasers has greatly improved since the 1990s. With the advancement of resonator technology, these lasers have become a notable alternative to traditional lamp-pumped lasers. One of the first widely used active laser media for high power operations, in the 1000 nm near-infrared range (NIR), was the Nd:YAG (Yttrium Aluminum Garnet), due to its prominent mechanical and thermal properties. However, it wasn't long until other neodymium-doped crystals grew in popularity. Crystals, such as $Nd{:}YVO_4$ (Yttrium Vanadate) and $Nd{:}GdVO_4$ (Gadolinium Vanadate), are a good alternative because of their broader absorption band and for being naturally birefringent, resulting in linearly polarized emission [1-2].

Extremely high efficiencies of 64% in optical and 72% in slope efficiency were reported by Damzen et al. (2001) using a so-called bounce resonator with the gain media $Nd{:}YVO_4$. The optical configuration used in their work had the laser beam at grazing incidence within the active media, resulting in a total internal reflection at the pump face of the crystal. The resonators presented in this paper uses a much bigger angle at the pump facet of 55.4°, allowing the cavity to achieve optimum efficiency despite the lower absorption cross-section of Nd:YLF.

Although bounces resonators have a better power scaling than end-pumped ones, they have less efficient fundamental mode operation due to the worse overlap between the pump and laser beam [3-4].

Nd:YLF lasers have a vast range of applications, some of them include material processing, medical and dental treatments, LIDAR, and even pumping of other lasers [5-8]. In comparison to neodymium-doped vanadates, fluorides generally show a smaller emission cross-section and smaller thermal shock parameter. However, their smaller emission wavelengths are of great interest for many applications such as retinal photocoagulation [9].

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The work of Wetter et al. (2015) showed the usage of a diode equipped with volume Bragg grating (VBG), operating at 797 nm, to side-pump an $Nd{:}YLF_4$ crystal in a double-beam mode-controlled (DBMC) laser. They were able to obtain 69 W of output power while having 65% of slope efficiency and optical efficiency of 60%, which until now was the best value achieved for this active medium.

In this work, we analyze the performance, both in beam quality and efficiency, of different single-bounce resonators pumped by a VBG equipped diode. With the VBG diode and an output coupler of 15% transmission, record optical efficiency was reached in a 10 cm long cavity.

II. Experimental setup

An $Nd{:}YLF_4$ crystal (Crystech, China), with dimensions of 13 x 13 x 3 mm^3, was side-pumped at 797 nm by a diode equipped with volume Bragg grating (VBG). In order to maximize absorption, the diode beam polarization was rotated, by a $\lambda/2$ wave plate, to be parallel to the c-axis of the crystal. The diode beam was focused into the crystal by a biconvex lens, with f = 25 mm. The crystal was pumped at a repetition rate of 5 Hz and a pulse duration of 353 µs,.

Figure 1 shows a scheme of the single-pass configuration used for all the resonators. The cavities consisted of a high reflector concave mirror (M1) and a flat output coupler (M2), with the $Nd{:}YLF_4$ pumped by the VBG equipped diode.

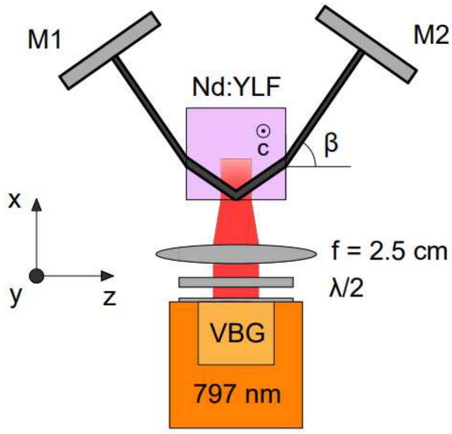

Fig. 1: Single-bounce resonator. The intracavity beam undergoes a total internal reflection at the pump facet with a 55.4 incidence angle.

For the first two resonators, a curved mirror of 150 mm radius was used in a 10 cm long resonator. Cavities 1 and 2 had output couplers of 15% and 10% transmission, respectively. With this configuration a beam size of 946.3 µm x 236.25 µm, in the horizontal and vertical directions, was obtained inside the crystal, as calculated using version

3.6 of the LASCAD software. The laser beam of these two cavities presented good quality in the y-direction while having a high horizontal M^2 value.

For the next 2 cavities, M1 was replaced by a 10,000 mm radius curved mirror and the overall length of the resonator was maintained at 10 cm. Cavities 3 and 4 had output couplers of 15% and 20% transmission, respectively. With the bigger radius of the curved mirror, the spot size of the beam inside the crystal was increased to 1493.6 µm x 792.65 µm, in the horizontal and vertical directions, respectively. With this configuration, it was possible to get a significant improvement in the quality of the beam in the x-direction.

For the last cavity, the combination of the curved mirror of 10,000 mm with a 15% transmission output coupler was maintained, but the distance between M2 and the crystal was expanded, resulting in a 30 cm long cavity. With this, the spot size inside the crystal was increased to 1617.5 µm x 1072.2 µm in the horizontal and vertical directions, respectively. The objective of the increase in the distance between the mirror M2 and the Nd:YLF crystal was to get an even larger beam size inside the crystal, difficulting the oscillation of modes of superior order and maintaining the laser beam in a near TEM_{00} operation.

III. Results

The maximum pump power for all resonators was fixed at 101.85 W, with a repetition rate of 5 Hz and a 353 µs pulse duration. This duty cycle was specified by the fabricant and has to be maintained in order to get optimal narrowing of the 797 nm emission line by the VBG coupled to the laser diode.

Cavity 1 (C1) generated 64.48 W of output power with an effective pulse duration of 335 µs, resulting in a 66.4% slope efficiency and an optical-to-optical efficiency of 63.31%. Replacing the 10% transmission output coupler in C1 by one of 15%, Cavity 2 (C2) produced a maximum of 62.73 W output power with a pulse duration of 330 µs, resulting in a 65.76% slope efficiency and an optical-to-optical efficiency of 61.59%. This resonator achieved good quality in the y-direction (M_y^2 of 1.47), while presenting an M_x^2 value of 11.5 in the horizontal direction.

By raising the radius of the curved mirror and maintaining the output coupler of C2, the configuration of Cavity 3 (C3) achieved 63.51% and 57.96% of slope and optical efficiencies, respectively. With an output power reaching 59.03 W and a pulse width of 310 µs, the laser operated with M^2 values of 1.76 x 3.12 in the y and x-directions, respectively. Using an output coupler of 20% while maintaining the 10,000 mm curved mirror, Cavity 4 (C4) showed a decrease in efficiencies when compared to C3. A 52.95 W of output power was reached with a pulse duration of 307 µs, resulting in a slope efficiency of 57.44% and an optical-to-optical efficiency of 51.99%. By extending the overall length of Cavity (C5) to 30 cm, the M_x^2 value was able to reach 1.97 in the x-direction, a 63% decrease from the value obtained in C3. This configuration generated 50.74 W of output power with a pulse duration of 303 µs, resulting in a 60.41% slope efficiency and an optical-to-optical efficiency of 49.82%.

Fig. 2 displays the curve of absorbed power versus emitted power for all the resonators mentioned above. The first four resonators had threshold conditions lower than 10 W of pump power, however, C5 had a threshold of 22 W.

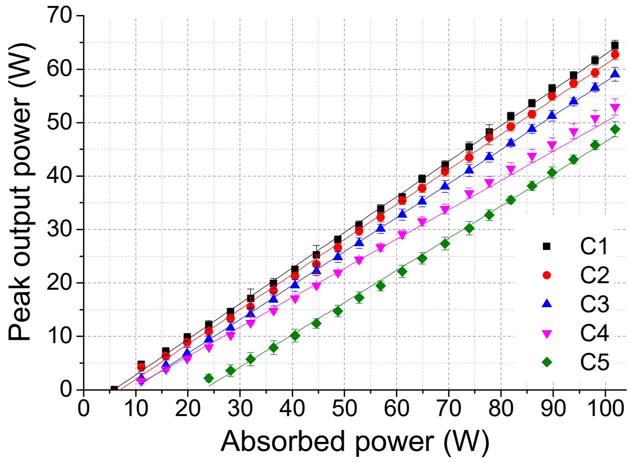

Fig. 2: Absorbed power versus peak output power of cavities C1, C2, C3, C4, and C5.

Fig. 3 shows the fit for the M_x^2 data of the cavities C2, C3, and C5, respectively.

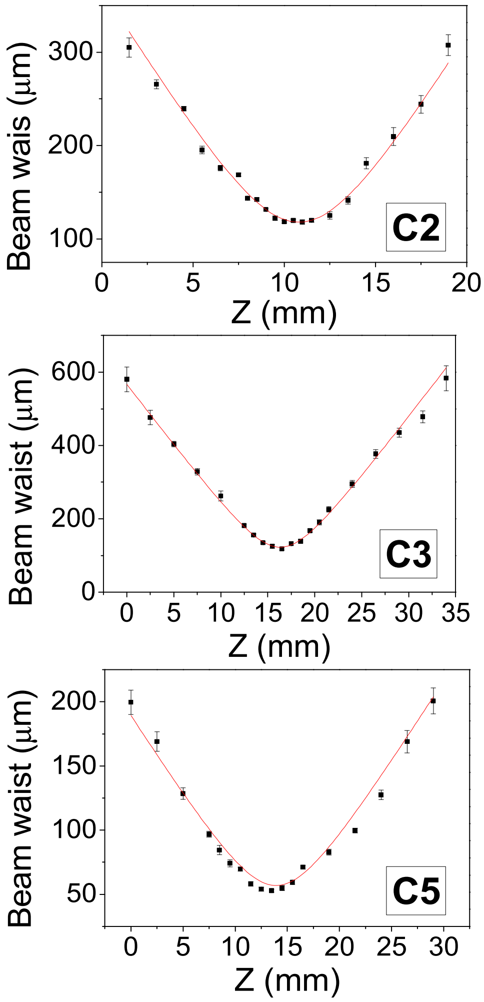

Fig. 3: Fits for the horizontal beam quality, resulting in values of M_x^2 of 11.52, 3.12, and 1.97 for the cavities C2, C3, and C5, respectively.

Table 1 displays the vertical beam parameters and the horizontal parameters generated from the fits shown in Fig. 3.

TABLE I: Values of M_x^2, M_y^2, w_{0x}, and w_{0y} for C2, C3, and C5.

	M_x^2	M_y^2	w_{0x} (µm)	w_{0y} (µm)
C2	11.52 ± 0.3	1.47 ± 0.2	122 ± 3.39	41.6 ± 2.28
C3	3.12 ± 0.12	1.76 ± 0.11	63.9 ± 2.67	50.8 ± 1.89
C5	1.97 ± 0.12	2.12 ± 0.13	50.7 ± 3.40	52.1 ± 2.74

While cavities 3, 4, and 5 presented a significant improvement in the horizontal beam quality, they also revealed an increase in the M_y^2 values. One of the factors contributing to the overall power reduction and the worsening of beam quality in the y-direction are the diffraction losses in the vertical direction that appear, at the edges of the Nd:YLF crystal, upon increasing beam size.

Fig. 4 displays the beam profiles for cavity 2 and cavity 5. These profiles were obtained using Newport's LBP series beam profiler.

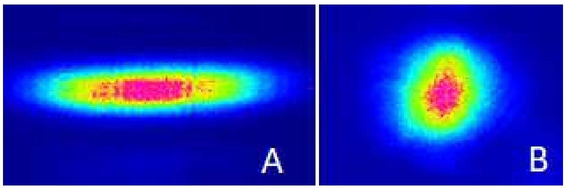

Fig. 4: (A) Beam profile of cavity 2 with an M^2 of 1.47 x 11.52 in the y and x-direction. (B) Beam profile of cavity 5 with an M^2 of 2.12 x 1.97 in the y and x-direction.

A complete overview of the cavities properties can be found in Table 2.

TABLE II: Cavities characteristics

	Peak Output Power	Output Pulse Width	Optical Efficiency	Slope Efficiency
C1	64.48 W	335 µs	63.31%	66.4%
C2	62.73 W	330 µs	61.59%	65.76%
C3	59.03 W	310 µs	57.96%	63.51%
C4	52.95 W	307 µs	51.99%	57.44%
C5	50.74 W	303 µs	49.82%	60.41%

IV. Conclusion

With the addition of a 10,000 mm radius curved mirror, it has been shown that we can greatly improve the overall quality of the laser beam, by enlarging its size within the gain medium, while maintaining slope efficiencies above 60%, despite the diffraction losses that were to be expected.

Considering all the resonators, the best results, in terms of output power, were obtained by using a 15% transmission output coupler. Despite not operating with a diffraction-limited beam in the x-direction, cavity 1 reached 64.5 W of output power and a record 66.4% slope efficiency and 63.31% of optical efficiency for a diode-side-pumped Nd:YLF_4 laser operating at 1053 nm, which fares well when compared to the previous record of 60% of optical efficiency [10].

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