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Efficient and compact diode-side-pumped Nd:YLF laser operating at 1053 nm with high beam quality

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Abstract
A very efficient, diode-side-pumped Nd:YLF laser is demonstrated using a compact cavity design based on total internal reflection inside the gain medium. With one pass through the crystal using a single bounce at the pumped face, efficiency in excess of 40% in multimode operation was measured, giving 6.6 W of output power for 16.2 W of pump power. Using two bounces inside the crystal, the beam quality was improved to fundamental mode with 4.2 W of output power for 16.2 W of pump power.

Keywords: solid state lasers, side pumping, Nd:YLF, beam quality

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Nd:YLF displays good qualities as a host material due to its superior thermo-optical characteristics, especially at 1053 nm, where the weak thermal lensing provides for a high quality output beam [1]. For *Q*-switched and amplifier applications, Nd:YLF is an attractive host material for near-infrared high power lasers because of its long storage lifetime. Recently, Nd:YLF has regained interest and some very high power lasers with good beam quality have been made with this material [2, 3]. The weak lensing observed under lasing conditions is a consequence of a refractive index decrease with temperature increase, creating a negative thermal lens, which partly compensates the positive thermal lens created due to expansion of the material [4]. Applications for Nd:YLF lasers include pumping of other solid-state lasers [5], medical treatment, industrial material processing, and LIDAR for pollution monitoring.

The development of novel laser designs is strongly focused on scaling the output power while keeping high conversion efficiency and high beam quality in fundamental mode operation. The overlap between the excited region and the volume occupied by the laser mode in the active medium is one of the most important elements in optimizing the efficiency and the beam quality of a solid-state laser. Longitudinal pumping geometries provide optimal mode matching, resulting in high efficiency and high beam quality. Using the longitudinal pumping scheme, slope efficiencies of 50% [6] or higher can be achieved for Nd:YLF laser systems in fundamental output. However, in this pumping configuration it is necessary to use a focused pump beam to maintain a good overlap between the laser and the pump beam, which restricts the pump power due to the risk of thermal fracture. One of the drawbacks of Nd:YLF is its low tensile strength (33 MPa), which limits the maximum pump intensity. Using a side pumping configuration, the pump power can be increased, but this configuration usually suffers from low efficiency when operating in TEM_{00} mode because of the poor overlap between the pump beam and the intracavity beam.

Slab laser designs with zig-zag optical path have been largely employed in laser development because of the advantages of these configurations, reducing the thermal induced focusing and birefringence [7]. Many design variations have been reported in the literature, in general, with the pump radiation quite distributed inside the crystal [8]. Zig-zag slab lasers can be scaled to the kilowatt level by

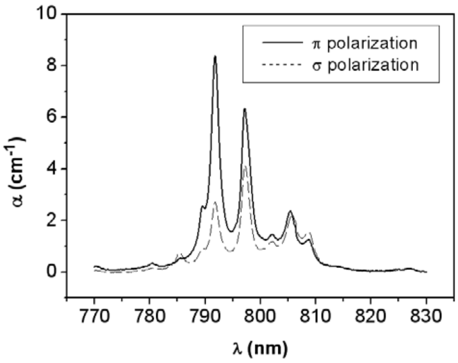

Figure 1. YLF absorption spectra for a Nd^{3+} concentration of 0.8 mol%.

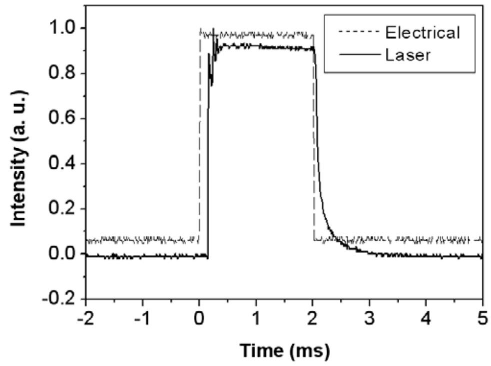

Figure 2. Laser behaviour in the time domain.

employing diode arrays [9], and they sometimes use total internal reflection instead of high reflectivity coatings to maintain the laser beam inside the slab. Some cavity designs using Nd:YLF slabs with multiple intracavity reflections have demonstrated high efficiency in TEM_{00} operation. Baer *et al* have demonstrated this with a tightly folded resonator, where each bounce of the beam path was configured to maximize the overlap with the radiation emitted from individual diode emitters [10]. Dergachev *et al* have developed a multipass slab laser system to improve the fundamental mode extraction. With this configuration, they have obtained high efficiency of 43% and high beam quality at the 1047 nm transition [11, 12].

When using a gain medium with high absorption, an interesting side-pumped geometry was proposed by Bernard *et al* using a grazing incidence configuration. They explored the high population inversion located in a shallow region near the pumped surface, where the intracavity beam bounces by total internal reflection [13]. Using $Nd:YVO_4$ with this configuration, Minassian *et al* achieved 68% optical-to-optical efficiency in multimode operation and 58% efficiency in fundamental mode using an asymmetric cavity geometry [14]. They have also demonstrated beam quality improvement with a double-bounce geometry using a four-mirror cavity [15].

This work differs from the common multipass or zig-zag slab laser design inasmuch as it uses a high, exponential inversion density at the pump face, similar to Minassian an co-workers, but in conjunction with Nd:YLF as active medium. However, since Nd:YLF has a smaller absorption coefficient than $Nd:YVO_4$, the effective absorption length is longer, requiring smaller incidence angles at the pump face in order to achieve good overlap with the pump radiation. The smaller incidence angles permit the use of the Brewster angle at the entrance of the beam into the crystal, which allows for crystals without any coating. Additionally, a second pass through the crystal is required for better overlap with the TEM_{00} mode. Using this technique, we can match the advantages of Nd:YLF, mainly low thermal lensing at 1053 nm, with the high efficiency and simplicity of the grazing incidence configuration.

The transition at 1053 nm has a much smaller emission cross-section, and 54% efficiency has been achieved in a longitudinal pumping scheme [16]. The optical-to-optical efficiency of more than 40% achieved in the setup reported here is, to our knowledge, the highest for side-pumped 1053 nm Nd:YLF lasers reported so far [12].

2. Experimental setup

The Nd:YLF crystal was grown in our in-house crystal growth facility by the Czochralski technique under high purity argon atmosphere. It had a relatively low dopant concentration of 0.8 mol%, generating an absorption peak of 8 cm^{-1} at 792 nm for light polarized parallel to the crystal c-axis (π polarization), as shown in figure 1. The crystal was cut and polished, resulting in a $14 \times 13 \times 4$ mm^3 slab with the c-axis along the y-direction. The crystal was mounted on a cooper support with thermal grease at the interface, ensuring good thermal contact, and circulating chilled water removed the heat from its bottom surface (14×13 mm^2 face).

Given our pumping configuration, seen in figure 3, it is very important to access the high absorption cross-section of the π-polarization in order to achieve a high inversion density at the pump face, where there is a good overlap with the laser mode. The effective absorption length is about 2 mm, and therefore it is not necessary to use a grazing incidence configuration as with $Nd:YVO_4$ [15]. We used incidence at 55°, which correspond to the Brewster angle at 1053 nm.

In order to achieve high absorption efficiency, the crystal was side pumped by a 20 W TM-polarized diode bar thermally tuned by a thermoelectric cooling system to operate at 792 nm, and the diode polarization was parallel to the crystal c-axis, thus matching its emission spectrum with the highest absorption coefficient peak of the crystal. With the purpose of avoiding fracture due to thermal stress, the diode was operated mostly in the quasi-continuous regime with a diode pulse width of 2 ms and a repetition frequency of 35 Hz, resulting in a duty cycle of 7%. Figure 2 shows the laser behaviour in this qcw regime. The laser has a delay of 0.14 ms to the diode electrical input; the measured laser pulse width was found to be 1.91 ms. The pump radiation was focused in the crystal by a 2.5 cm focal length spherical lens, resulting in a spot size of 4.2 mm $\times$ 97 μm in the horizontal and vertical directions, respectively.

Two experiments with different cavity designs were performed in order to demonstrate the beam quality

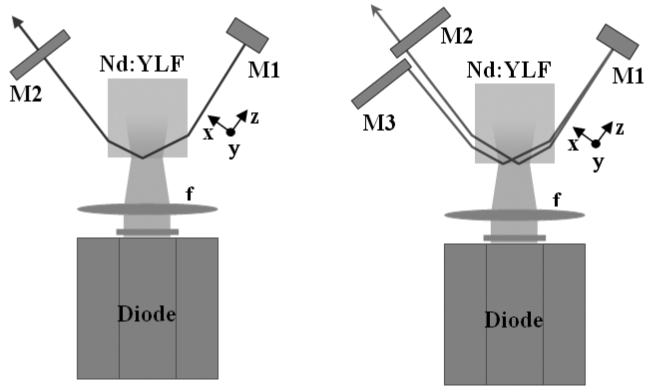

Figure 3. Schematic diagrams of the cavity configurations. Single-bounce resonator (left) and double-bounce resonator (right). M2 is a flat output coupler, M1 a curved folding mirror, and M3 a flat, high reflector; f is the pump focusing lens.

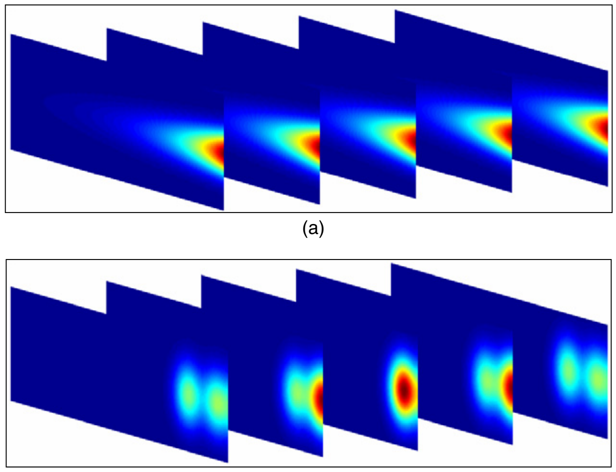

Figure 4. Shown are five cross-sections of the diode-side-pumped region of the crystal: (a) normalized pump distribution; (b) pump face shown with two parallel TEM_{00} modes undergoing total internal reflection.

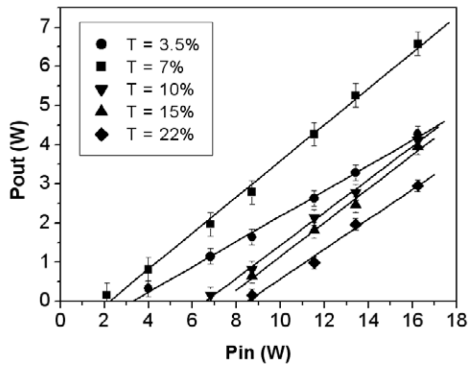

Figure 5. Output power at 1053 nm through M2 as a function of pump power in the single-bounce configuration using different output couplers M2.

improvement by increasing the overlap between the pump and intracavity beams in side-pumped lasers with multiple-pass configurations. The first experiment, shown in the left-hand side of figure 3, was carried out using a cavity with a single-pass configuration and the second experiment was performed with a double-pass configuration, as shown in the right-hand side of figure 3.

In the single-bounce configuration, a hemispherical cavity was mounted using two mirrors: a 50 cm radius of curvature high reflector mirror and a flat output coupler. The crystal was mounted in Brewster angle configuration to minimize reflection losses at its surfaces. Laser oscillation at 1053 nm was along the crystal x-axis. The total size of the cavity was, approximately, 8 cm × 8 cm.

The double-bounce configuration was mounted using a resonator with a double-pass design by means of two total internal reflections at the pumped face. The same crystal was used adding a third mirror to the cavity: a flat high reflector mirror.

In figure 4, a simulation of the laser beam passing through the pump region is shown for the double-bounce configuration. The beam waist inside the resonator was simulated using a MATLAB program based on the ABCD ray-matrix [17] for Gaussian beam propagation. As can be observed from figure 4, there exists a good overlap between the area occupied by the two beams and the area inverted by the pump radiation. In this simulation are shown crystal cross-sections of the pumped region, as illustrated on the right of figure 3, along the laser propagation direction for the pump absorption (figure 4(a)) and the laser beam (figure 4(b)). The simulated sections are perpendicular to the pump face and parallel to the y-direction.

3. Results and discussion

In the single-bounce experiment, the laser presented maximum efficiency with the 7% transmission output coupler. It achieved 6.6 W of multimode output power at 1053 nm for 16.2 W of pump power, which results in a 41% optical-to-optical efficiency and a 46% slope efficiency (figure 5). The output beam was multimode with M^2 of 43.3 × 2.15 in the horizontal and vertical directions, respectively. In this configuration, cw operation was also tried without improvement of the crystal's refrigeration (only the bottom surface was refrigerated). At 17.1 W of pump power the crystal fractured due to thermal stress.

With two bounces at the pumped crystal surface, using a double pass through the gain medium, the output beam quality was improved. Different modes could be observed according to the cavity alignment, as shown in figure 6, depending on the separation between the two beams.

The laser presented a TEM_{30} output beam with M^2 of 6.2 × 2.2 in the horizontal and vertical directions, respectively, using a 15% output mirror transmission, without significant loss of output power (6.4 W, figures 6(b) and 7(a)), when compared with the single-pass configuration. A TEM_{10} profile was observed with 4.9 W of output power (figure 6(c)) and fundamental mode (M^2 of 1.5 × 1.4 in the horizontal and vertical directions, respectively; figure 8) was achieved with 4.2 W of output power. In this case, pump power was 16.2 W,

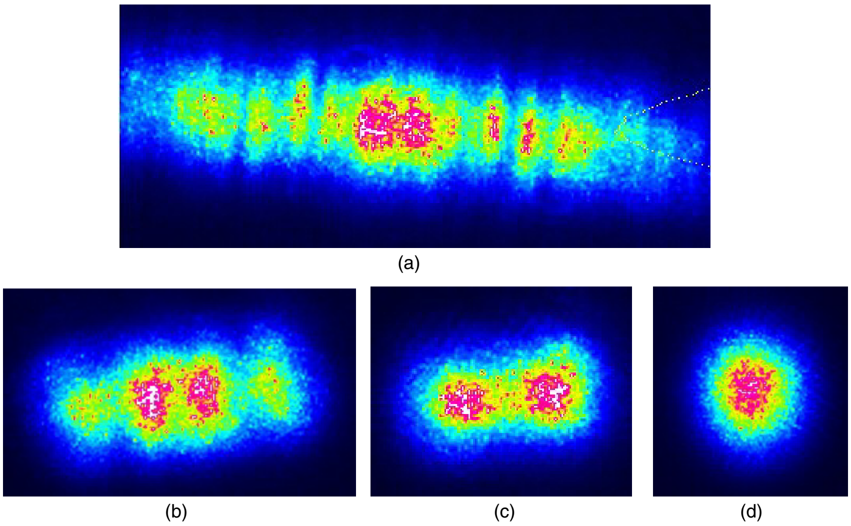

Figure 6. Beam profiles (a) multimode output beam from the single-bounce configuration; (b) TEM_{30} mode obtained with the double-bounce configuration at the maximum output power of 6.4 W; (c) TEM_{10} mode obtained in the double-bounce configuration with 4.9 W; and (d) fundamental mode obtained with the double-bounce configuration with 4.2 W.

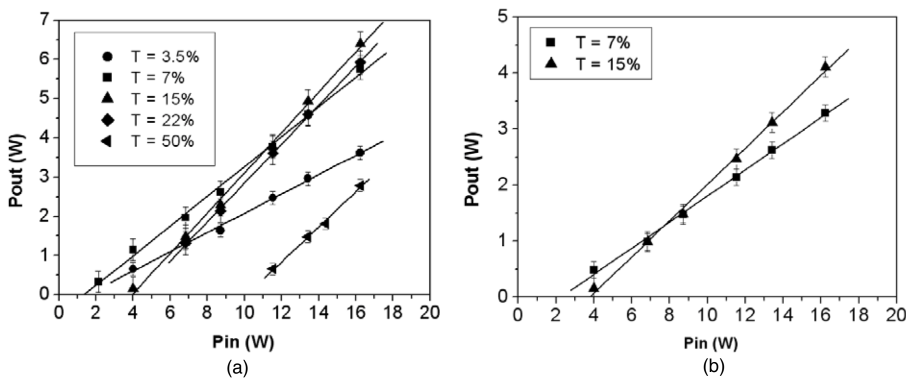

Figure 7. Output power at 1053 nm as a function of pump power for the Nd:YLF laser in double-bounce configuration for multimode (a) and TEM_{00} mode (b).

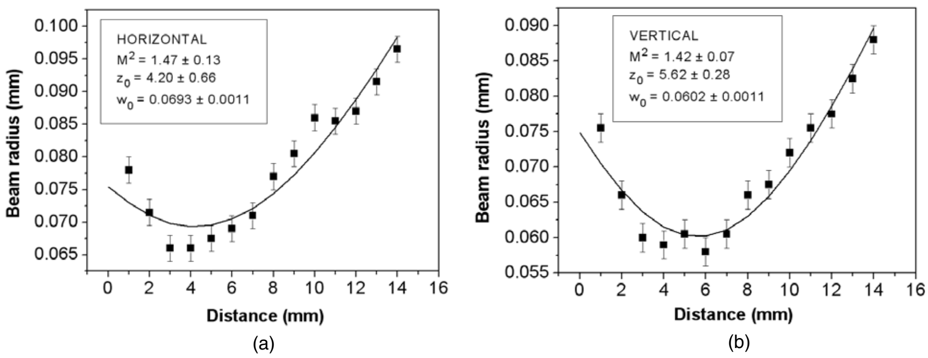

Figure 8. Laser beam behaviour for horizontal (a) and vertical (b) propagation for the TEM_{00} mode obtained with the double-bounce configuration.

resulting in 26% optical-to-optical efficiency and 32% slope efficiency (figures 6(d) and 7(b)).

A Findlay–Clay analysis was performed in order to estimate the cavity round-trip losses. Figures 9(a) and 8(b) show the pumped power threshold as a function of the mirror transmission for single- and double-bounce configurations, respectively. From figure 9, the round-trip cavity loss for the single-bounce configuration was calculated to be 2.6%. For the double-bounce configuration, the round-trip cavity loss was found to be 7.1% in multimode operation.

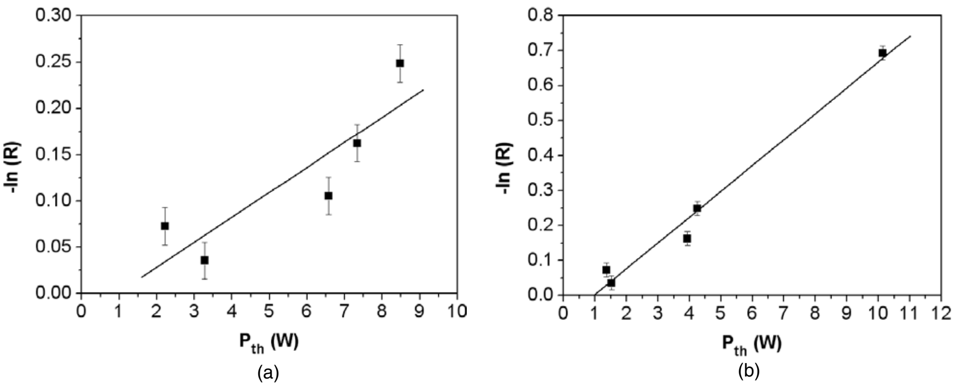

Figure 9. Threshold pump power as a function of transmission loss of mirrors for (a) single-pass and (b) double-pass configuration.

4. Conclusions

A highly efficient and compact diode-side-pumped Nd:YLF laser operating at 1053 nm was demonstrated. The laser presented 6.6 W of output power, resulting in a optical-to-optical efficiency of 41%, which is, to our knowledge, the highest reported so far for side-pumped Nd:YLF lasers operating at the 1053 nm transition. It was shown that a double pass through the gain medium improves the output beam quality. Using a double-bounce configuration, the beam quality could be enhanced by a factor of seven without significant loss of output power (6.4 W), when compared with the single-bounce configuration. Fundamental mode was achieved with 4.2 W of output power. The cavity presented permits power scalability and compactness by using other diodes disposed laterally to the gain medium.

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