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100 W continuous linearly polarized, high beam quality output from standard side-pumped Nd:YAG laser modules

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ABSTRACT

Dynamically stable operation with joined stability zones of a linearly polarized resonator is shown for a laser containing two diode side-pumped Nd:YAG rods. The unpolarized resonator generated 115 W of output. When polarized by a Brewster plate, it reached 100.5 W of output power at a beam quality $M^2 < 2$. Best measured beam quality was of 1.1 and 1.3 in the x and y directions respectively, with 76 W of 95% polarized output. The output power achieved is, to our knowledge, the highest reported for continuous polarized, fundamental-mode lasers using standard side-pumped Nd:YAG modules.

1. Introduction

Building lasers with high output power and good beam quality has always been a prominent goal of laser research. Solid-state lasers with high average powers and good beam quality are required in a great number of applications such as materials processing, remote sensing, pump lasers for optical parametric oscillators and frequency conversion [1,2]. Nd:YAG is the most common active material for these purposes because of its favorable optical and thermal characteristics and the availability of cheap, high-power pump diodes [1,3]. Although many different pumping schemes and laser types are available nowadays, diode-side pumped Nd:YAG rod lasers (DPSSL) are a very competitive technology because of their proven reliability, power scalability, simplicity, availability and low cost of components [4–6]. From the commercial point of view, there are nowadays many vendors that offer side-pumped Nd:YAG modules with several hundred watts of output power at a price of approximately ten dollar per watt of output power including power supply, which represents the most economical way to build a multimode laser with more than 100 W. However, the growing demand for high quality, continuous power laser beams has led to more sophisticated designs such as MOPAs or high power fiber lasers, which are more complicated, expensive and prone to failures such as catastrophic damage caused by back reflections [7,8]. Additionally, polarized laser beams are of utmost importance nowadays for many manufacturing applications such as surface texturing, drilling and cutting of metals [9–15].

It is therefore of great interest to the scientific community to investigate further methods to incorporate high-beam quality into solid-state lasers made with standard modules and to push their output power beyond 100 W with the additional option of a polarized output beam.

Magni [16] has shown that it is possible to achieve fundamental mode operation in a side pumped rod if the TEM_{00} spot radius inside the rod, w_{30}, is about 50–83% of the rod radius. This size of the lowest order mode still prevents significant diffraction losses and avoids higher order modes from oscillation. However, fundamental mode size is limited by thermal optical effects inside the rod, namely thermal lensing and thermal birefringence. In the case of Nd:YAG, maximum TEM_{00} spot size inside the rod is 1.1 mm due to thermally induced birefringence, regardless of the size of the laser rod [17]. This limits the output power for TEM_{00} operation despite the fact that current crystal growth techniques allow obtaining large Nd:YAG rod diameters.

A way of scaling the output power is the use of several rods. Specifically using two identical rods has proven a very successful concept because in this way the thermally induced birefringence of one rod can be compensated inside the other rod by the use of a polarization rotator between both rods [18]. We also investigated laser designs that used more than two modules but, to our knowledge, none of those are single transversal mode. Several high power (but not polarized) TEM_{00} lasers with two side-pumped rods operating at 1064 nm are found in literature: Hirano et al. [19] obtained a pulsed 208 W TEM_{00} laser with two rods utilizing a specially designed high power pump optics, which provided a total of 1100 W from 40 stacked diode arrays focused by aspheric cylindrical lenses into slab waveguides, which transported pump radiation

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to the interior of a diffuse pump cavity. Ostermeyer et al. [20] obtained 182 W in the quasi-cw regime. Kugler et al. [21] obtained pulsed 145 W in a resonator with a special adaptive mirror containing lamp pumped rods. Konno et al. [22] obtained 153 W with $M^2 = 1.18$ in cw operation with two specially designed diffuse cavity modules where radiation from the diodes was transported by waveguides to the rods. Ma et al. [23] obtained 124 W in the cw regime with $M^2 = 1.4$ from two self-developed diode side stagger-pumped laser modules in a V-shaped resonator containing intracavity lenses. Zhang et al. [24] obtained 82.3 W in the cw regime. Yang [25] obtained 41 W in cw operation.

Regarding linearly polarized TEM_{00} lasers, Xu et al. [1] obtained 101.4 W with $M^2 = 1.14$ in the quasi-cw regime and utilizing a special threaded rod for improved heat transfer and with carefully chosen diodes to match the Nd:YAG absorption peaks. Regarding polarized continuous operation, Konno et al. [22] obtained 105 W in cw operation with $M^2 = 1.08$ using complex pump modules, containing special pump waveguides as mentioned above.

So far, the best reported results, to our knowledge, for two standard transversally pumped rods and polarized continuous output, are 61 W with M^2 of 1.6, using a Brewster plate for polarization [18,26]. In the present work, standard diode side-pumped solid-state modules are employed. We demonstrate continuous polarized output of 100.5 W with M^2 of 1.8 using a Brewster plate and 76.3 W with M^2 of 1.2 when using a TFP polarizer.

It is well known that any stable resonator can be attributed to one of two possible stability zones, which are a function of the mirror radii and the distance between them. When the resonator includes a variable lens, such as the thermal lens inside the laser rod, the same resonator may pass through both zones as a function of the lens' focusing power. According to Magni [16], a dynamically stable resonator (DSR) always has two stability zones of same width and with the same minimum TEM_{00} spot size, w_{30}, at the rod center. This minimum spot size can be calculated as a function of the width of the zones in terms of dioptric power:

$$w_{30}^2 = \frac{2\lambda}{\pi} \frac{1}{|\Delta 1/f|} \quad (1)$$

where f is the focal length and λ the laser wavelength. $\Delta 1/f$ is the width of the stability zone in diopters. If high output powers in fundamental mode are to be achieved, then w_{30} must be as large as possible. However, Eq. (1) sets a clear limit to the maximum value of w_{30}, which occurs when the stability zone width becomes too small for stable laser operation. In the case of Nd:YAG lasers, thermally induced birefringence further decreases the maximum achievable spot size because stable laser operation requires that the stability zone is wide enough to accommodate both, tangential (f_Θ) and radial (f_R), thermally induced focal lenses. Literature gives an approximate value of $f_\Theta/f_R = 1.2$ which implies in the narrowest stability zone being $\Delta 1/f = 0.18_* f$ [27,28]. Substituting this value into Eq. (1) results in the maximum, birefringence limited TEM_{00} spot size in the laser rod:

$$(w_{30}^{BL})^2 \approx 3.5\lambda f \quad (2)$$

It becomes clear at this point that birefringent compensation methods, such as using a half-wave-plate between two identical DPSSL modules, allow for increasing the output power because they allow to overcome the limit given by Eq. (2) [19].

Cerullo et al. compared resonators with separated and joined stability zones and among his main results was the achievement of higher output power for the resonators with joined zones [27]. Resonators with joined stability zones can be easily achieved with symmetric resonators that use the same mirror radii, $R_1 = R_2$, at the same distances, $L_1 = L_2$, from the rod. In resonators with joined stability zones, it is possible to operate the radial thermal lens in one zone while the tangential lens operates in the other zone. However, the fact that both zones are joined does not remove the instability at the middle of the interval and a part of the beam will experience a dioptric power that corresponds to this instability. In practice, this instability can be easily avoided by a small realignment of the cavity [2,28].

Here we developed a laser based on two standard laser modules (DPL-1064-S1-0075, HTOE Optoelectronics) containing a $\varnothing$3 mm × 78 mm long Nd:YAG crystal rod doped with 0.6 at.% neodymium that was side pumped with up to 225 W optical power at 808 nm by means of 12 diode bars arranged in groups of 4 in a threefold geometry.

2. Materials and methods

The laser modules use a well-known pumping scheme where light from the diode bars is directly coupled in the laser rod that is located inside a quartz tube that retains the cooling water, as depicted in Fig. 1.

The laser was assembled with both modules as close as possible, containing a half wave plate between them to achieve birefringence compensation as shown in Fig. 2.

The set of two modules with the wave plate was characterized regarding its thermal lens by passing a collimated He-Ne beam trough the set-up while applying current to the modules. The radial and tangential components of the lens were measured by combining a slit aperture and a polarizer as described in [28].

The cavity of choice was a symmetrical convex-convex resonator for two reasons: first, it allows for minimum misalignment sensitivity at the maximum pump power and second, it is a very compact cavity [2]. The mirror radii (R_1 and R_2) were −10 cm

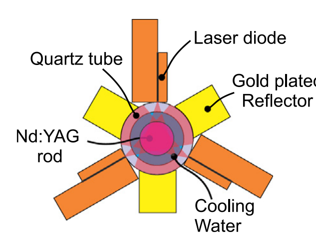

Fig. 1. Diagram displaying a cross-sectional view of the pumping scheme in the laser module.

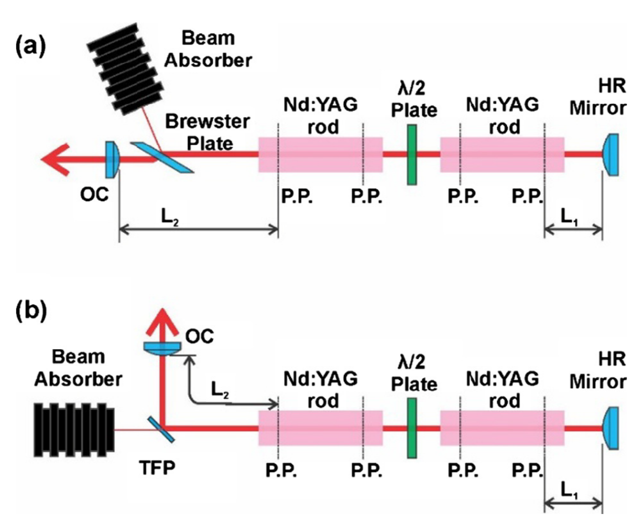

Fig. 2. Resonator configuration. (a) Brewster plate polarized; (b) TFP polarized. *P.P.* denotes the principal planes of the rods.

and the distances from the mirrors to the first principal plane of the laser rods (L_1 and L_2) were 19.7 cm. Output coupling was T = 30%. Either a Brewster window or a thin–film polarizer (TFP) were used to achieve a polarized output beam as shown in Fig. 2.

The stability diagram, calculated beam waist within the joined stability zones and sensitivity to misalignment are shown in Fig. 3. To ensure joined stability zones, the distances L_1 and L_2 were finely tuned until no power drop in output power was observed in the transition between zones.

3. Results and discussion

Thermal lens measurements are shown in Fig. 4. It can be seen that tangential and radial polarizations do not vary much along the horizontal and vertical axis, which is an indication of homogeneous pump distribution. In addition, f_Θ/f_R is less than 1.2, which demonstrates clearly that birefringence compensation is working.

At maximum pump power, the unpolarized resonator provided 115 W of output power with a M^2 value of approx. 3. With a Brewster plate inside the resonator it reached 100.5 W with corresponding M^2 values of 1.7 and 1.9 in the vertical and horizontal directions, respectively with a gaussian-like profile and 91% of the output beam being polarization in the vertical direction. Using the TFP, the best result was 76.3 W of output power in a 95% linearly polarized output beam with good beam quality: The M^2 beam quality was 1.1 and 1.3 in the horizontal and vertical directions, respectively, as measured with a scanning-slit beam analyzer (Beamscope P8, Dataray Inc), using the second moment method (shown in Fig. 5). A comparison of the output power and corresponding M^2 values is shown in Fig. 6.

The less polarized Brewster window configuration had the benefit of higher output power and stable beam quality as a function of pump power throughout the whole stability interval, whereas the TFP polarized resonator showed lower output power and a beam quality that improved close to the border of the stability intervals

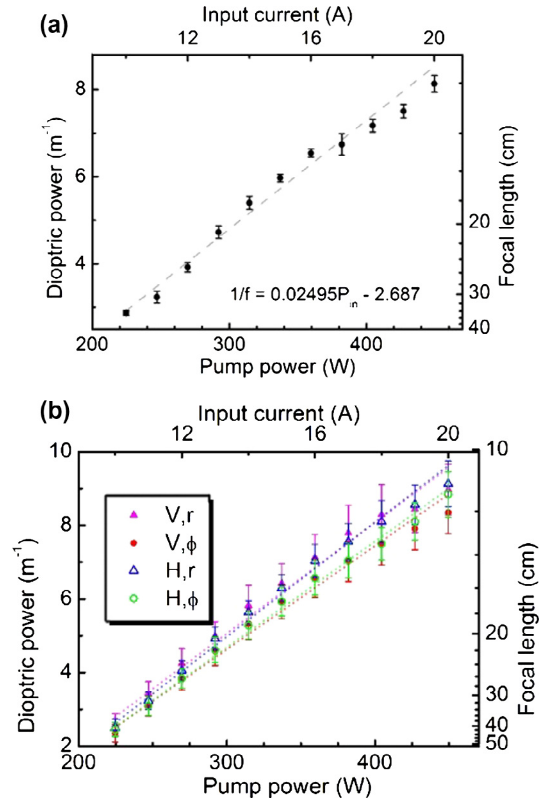

Fig. 4. (a) Unpolarized thermal lens measurements and (b) polarized measurements separated in radial (r) and tangential (Φ) polarization measured along the vertical (V) and horizontal (H) axis.

as shown in Fig. 7. Clearly seen is the increase in beam quality at the transition between both stability zones around 390 W of pump power, and again at the end of the last stability zone close to 450 W

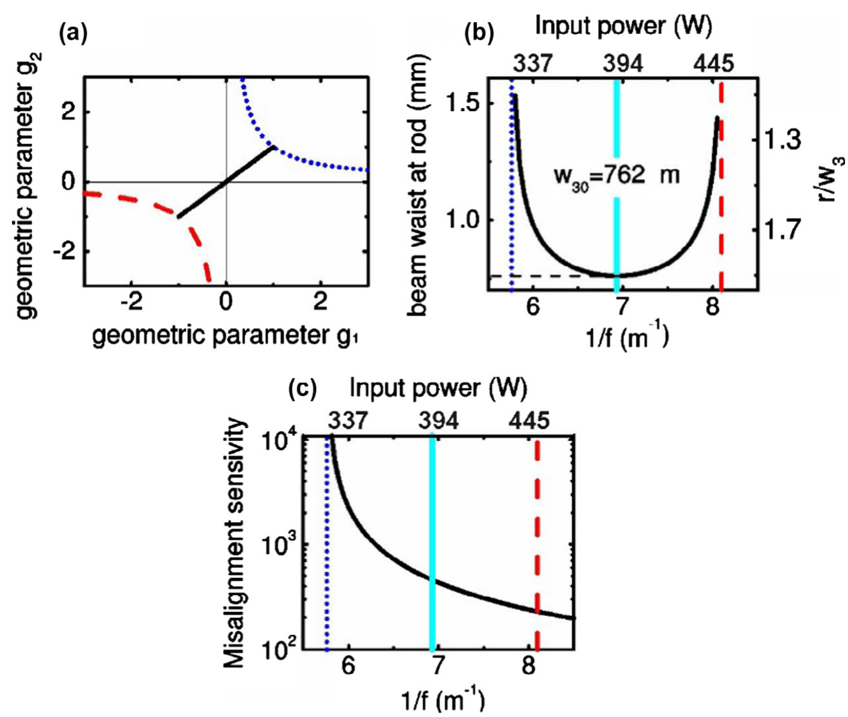

Fig. 3. Black lines represent the behavior of the laser as a function of 1/f. (a) Stability diagram. (b) Calculated beam waist inside the rod as a function of the dioptric power showing a minimum of w_{30} = 762 μm. (c) Calculated sensitivity to misalignment (dotted line $g_1g_2 = -1$; dashed line $g_1g_2 = 1$; solid vertical line in the middle: border between both stability zones).

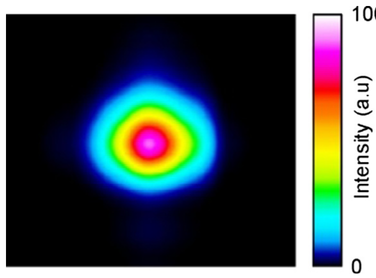

Fig. 5. Intensity profile plot of the TFP polarized beam with $M^2 = 1.1$ (horizontal) and 1.3 (vertical) at 76 W of output power.

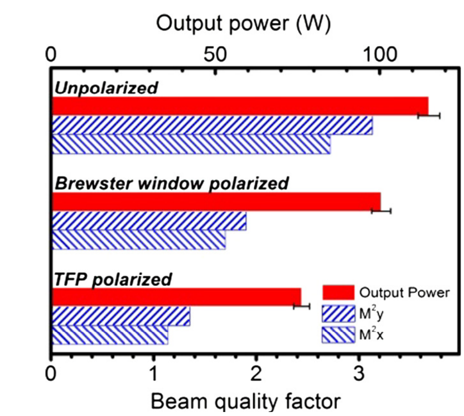

Fig. 6. Comparison of the results for different resonator configurations.

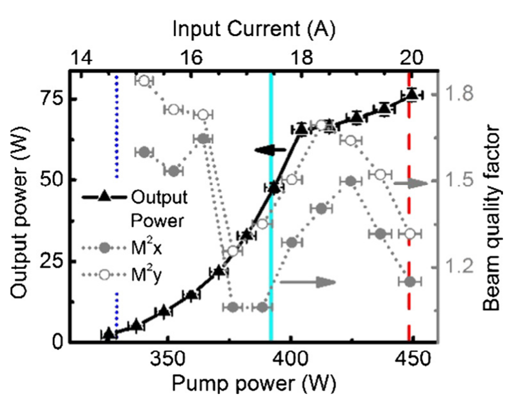

Fig. 7. TFP linearly polarized laser output power and beam quality factor. Vertical lines represent the calculated limits for the stability zones (dotted line $g_1g_2 = -1$; dashed line $g_1g_2 = 1$; solid vertical line in the middle: border between both stability zones).

of pump power. No dip in the in-out curve is observed at the transition between both zones close to 390 W of pump power.

We noticed that the TFP responds critically to the slightest misalignment from exact 45°, showing a very small acceptance angle. Our assumption is that the lower power obtained in the TFP resonator is in part due to the difficulty in obtaining good TFP alignment considering the strong divergence of the beam inside the convex-convex resonator.

For comparison we operated the two modules at maximum pump power in an as short as possible plane-plane cavity with 30% output coupling and obtained 217 W of highly multi-mode unpolarized output. Therefore, the three resonators tested here which were unpolarized, Brewster plate polarized and TFP polarized TEM_{00} demonstrated 53%, 47% and 35% of extraction efficiency, respectively, when compared to unpolarized multimode output. Corresponding electrical to optical efficiencies were 12.0%, 10.5% and 7.9%.

Finally, we compare the equivalent brightness, defined by output power divided by the square of the beam quality, of the different resonators. The equivalent brightness of the Brewster and TFP polarized resonators is 270 W/mm^2 mrad^2 and 464 W/mm^2 mrad^2, respectively. This represents a more than twofold increase in brightness when compared to the results from literature (207 W/mm^2 mrad^2 [26]).

4. Conclusion

We achieve, to our knowledge, the highest output power for a linearly polarized, continuous laser operating in single transversal mode that uses standard, diode-side-pumped Nd:YAG-rod modules. Increase in brightness with respect to previous, comparable results is more than twofold. This opens the way for sub 10 dollar per watt single-mode and polarized lasers in the hundred-watt output power class.

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