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A high-power diode-pumped Nd:YVO_4 slab amplifier with a hybrid resonator

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Abstract

We demonstrated a compact and efficient in-band diode-pumped Nd:YVO_4 partially end-pumped slab (Innoslab) nanosecond amplifier based on a hybrid resonator. For the seeder source, a-6 W, 5 ns Q-switched laser with a repetition rate of 30 kHz was obtained with beam quality factors $M^2 < 1.3$. A beam-shaping system consisting of cylindrical lenses was designed according to the different sizes of the active medium in two orthogonal directions.
A maximum average output power of 77 W was obtained. The optical-to-optical efficiency was 27.9%. The beam quality factors M^2 in the unstable and stable directions were 1.52 and 1.36, respectively.

Keywords: Nd:YVO_4, nanosecond amplifier, hybrid resonator

(Some figures may appear in colour only in the online journal)

1. Introduction

High-average-power, nanosecond-pulse, all-solid-state laser systems that operate in the infrared are of fundamental interest for both scientific and industrial applications, such as high efficiency nonlinear optics [1], the generation of THz waves [2], materials processing [3–5], and optical parametric processes [6]. Instead of scaling up the output power of an oscillator, which would be limited by the thermal effects and damage threshold of the gain medium, a reliable solution is a master oscillator power amplifier (MOPA).

In order to obtain high power and good beam quality, various designs of MOPA have been developed, such as single-pass, double-pass, and multi-pass amplifiers. Although this is useful, the cross-section of the laser beam remains largely unchanged while it passes through the gain medium, which is dangerous to the gain medium with increasing amplifier power. Subsequently, Du *et al* invented the partially end-pumped slab laser (Innoslab) [7], which has also proved to be useful for slab amplifiers. First, due to a good overlap of the amplified and pumped modes, the intrinsic efficiency is high. Second, there is the key feature of beam expansion during amplification, which keeps the intensity roughly constant and away from damage thresholds. Third, on account of good thermal management, the amplifier beam quality is good. In addition, for its characteristics, the setup is compact [8]. Therefore, many attractive results have been obtained using the Innoslab amplifier structure. In 2007, Zhe Ma *et al* reported an average power of 28.8 W at a repetition of 100 KHz with a pulse width of 15 ns [9]. The same year, they obtained a maximum output power of 35.2 W in cw operation by amplifying the seeder power of 4 W [10].

The Nd:YVO_4 crystal has exhibited a large gain cross-section and high single-pass gain, which are valuable for the generation of high average output power with high efficiency for nanosecond seeder amplifiers.

In this paper, we present an in-band diode-pumped Nd:YVO_4 partially end-pumped slab (Innoslab) nanosecond amplifier based on a hybrid resonator. An average power of 77 W at a repetition rate of 30 kHz was obtained. The optical-to-optical efficiency was 27.9%. The beam quality factors M^2 in the unstable and stable directions were 1.52 and 1.36, respectively.

2. Design of the amplifier

The schematic of the amplifier design is shown in figure 1, and is similar to the schematic in [10]. The amplifier resonator consists of the input mirror M1 and the output mirror M2. M1 is a cylindrical mirror with a radius of $R1$, and is coated for high reflection (HR) at the seeder beam and high transmission

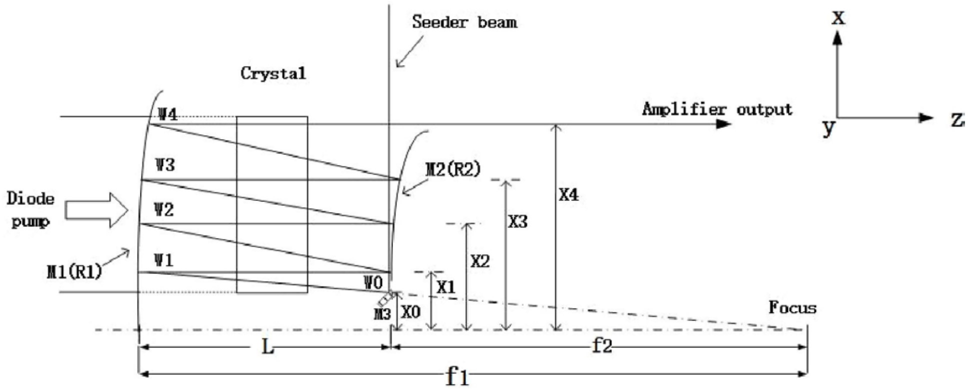

Figure 1. Schematic of the eight-pass slab amplifier geometry.

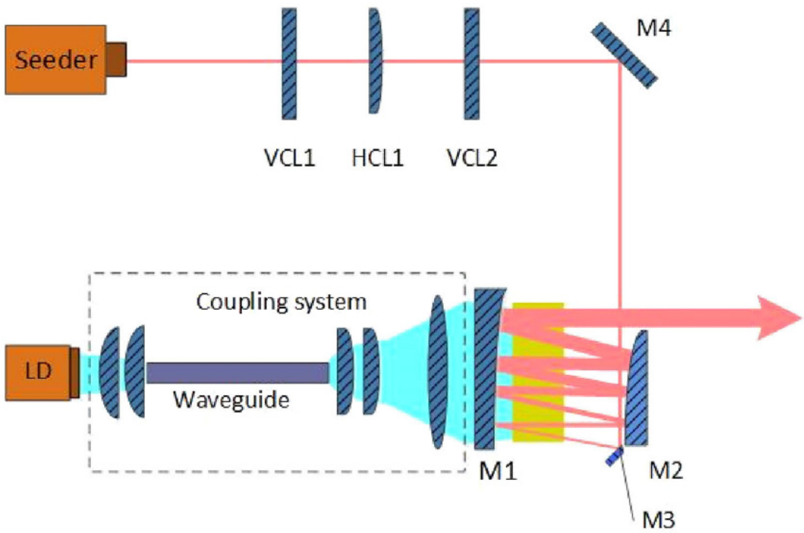

Figure 2. Schematic of the experimental setup.

(HT) at the pump beam. M2 is also a cylindrical mirror with a radius of $R2$, and is coated for HR at the seeder beam. M1 and M2 build up a stable cavity in the Y–Z plane and an off-axis unstable positive confocal cavity in the X–Z plane. The size of the laser crystal is $a \times b \times c$, and the length of the pump line along the x-direction is the same as the width of the crystal. In theory, the length of the cavity is $L = (R1 + R2)/2$. The equivalent magnification $M = |R1/R2| > 1$ in the unstable direction. The edge of the crystal is deviated from the optical axis of the confocal cavity for a distance to prevent oscillation building of the hybrid resonator. The seeder beam propagation is off-axially reflected by mirror M3 into the plane of the pumping line and passes through the end-pumped laser crystal eight times. M3 is a 45° flat mirror, which is coated for HR at the seeder beam and is very close to the output mirror M2.

In the x-direction, the waist of the seeder beam is shaped at a distance from M3 that is the same as the distance between M3 and the focus of the confocal cavity. As shown in figure 1, the positions from the optical axis and the radius of the seeder beam at the entrance of the amplifier (mirror M3) are X_0 and W_0, respectively. Due to the magnification M, after each round trip, the beam size in the plane of the pumping line is enlarged by a factor of M. In this case, after m round trips though the crystal,

$$X_m = X_0 M^m, \tag{1}$$

$$W_m = W_0 M^m. \tag{2}$$

The length of the crystal along the x-direction, b, should satisfy

$$b \geqslant X_0 M^m - X_0 + W_0 + W_0 M^m. \tag{3}$$

The length of the beam diameter covering the pump line along the x-direction can be calculated as follows:

$$b' \approx 2*(2W_0 M + 2W_0 M^2 + 2W_0 M^3 + 2W_0 M^4). \tag{4}$$

In order to take full advantage of the diode pump energy, the value of b' should approach the length of the pump line. Beam expansion is a key feature of the concept, because it yields a constant saturation and therefore efficient operation while simultaneously keeping the intensity evenly away from damage thresholds and allowing for small nonlinearity. Although eight passes through the crystal are accomplished, it is still a single-pass amplifier, because a new section of the pumped volume is saturated at each pass, thereby collecting the smallest possible aberration per overall gain.

In the y-direction, the waist of the seeder beam is shaped at the entrance of the amplifier (mirror M3) to match the cavity

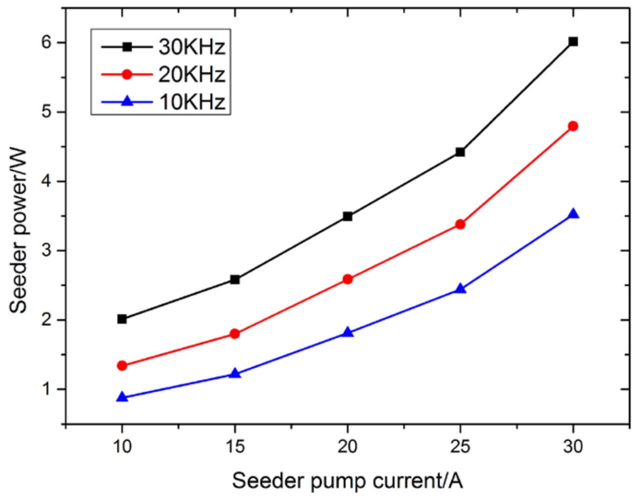

Figure 3. Output power of the seeder laser.

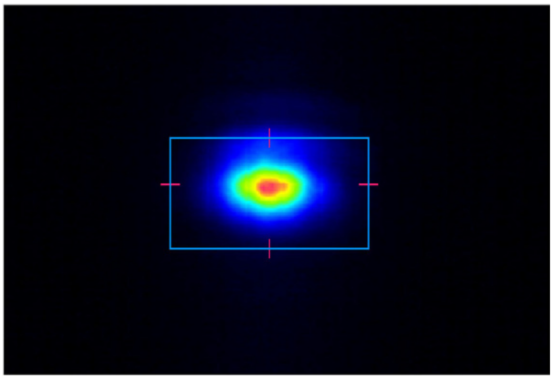

Figure 4. The beam shape of the shaped seeder laser at the amplifier entrance.

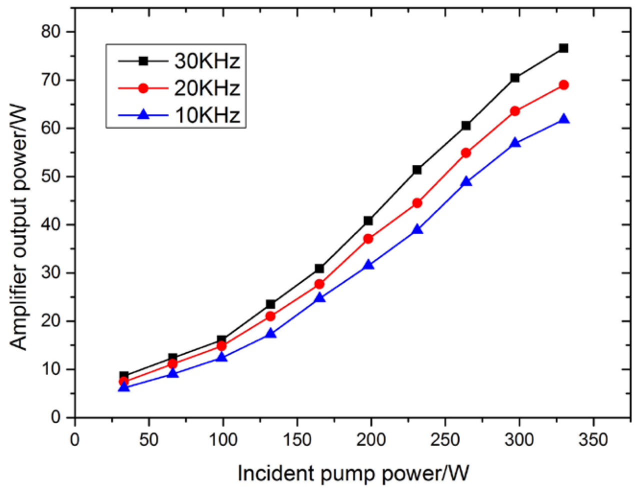

Figure 5. The amplifier output power versus the incident pump power at different frequencies.

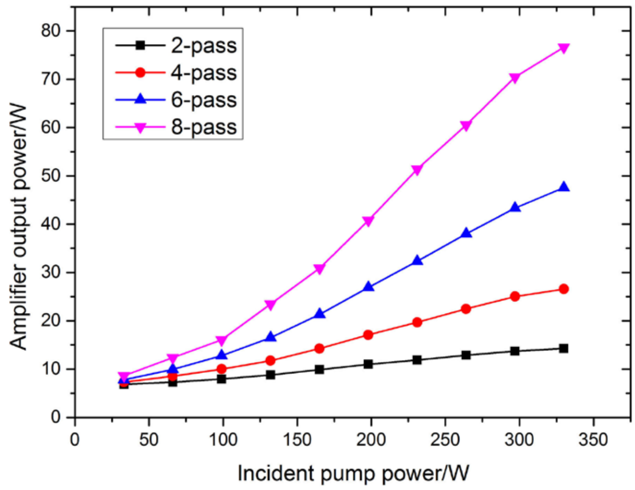

Figure 6. The amplifier output power versus the incident pump power with different even numbers passing through the crystal at 30 kHz.

mode. Because of the thermal lens in the *y*-direction, the mode is self-reproduced.

3. The experiment setup and results

The experimental setup of the amplifier is shown schematically in figure 2. The laser diode stack consisted of six bars with the central wavelength fixed at 880 nm by adjusting the cooling water temperature. The emission from each diode laser bar was individually collimated by a micro lens, which was coupled into a coupling system. The coupling system was composed of four cylindrical lenses, a rectangular waveguide, and a battery of lenses. The beam coupling led to a pump power loss of ~12%. A homogeneous pumping line of ~0.3 mm × 18 mm was coupled into the central part of the (18 mm × 10 mm × 1 mm) Nd:YVO_4 crystal by the coupling system. The Nd:YVO_4 crystal with 0.3at% Nd-doped was *a*-cut with the *c* axis along the 18 mm direction. Indium foil was used for uniform thermal contact and cooling. The laser crystal was mounted between two water-cooled copper heat sinks with two large faces (18 mm × 10 mm). The heat conduction inside the laser crystal was quasi-1D. The two 18 mm × 1 mm surfaces were polished and anti-reflection coated for 880 nm and 1064 nm.

Two cylindrical mirrors M1 and M2, with curvature radii $R1 = 500$ mm and $R2 = -350$ mm, respectively, were used as the amplifier resonator. Both of them were coated for HR at 1064 nm and M1 was also coated for HT at 880 nm. The equivalent distance between the two mirrors was $L = (R1 + R2)/2 = 75$ mm. In the *x*-direction, a positive branch confocal off-axis unstable resonator was formed with magnification $M = |R1/R2| = 1.43$. The thermal focal length of the crystal was ~200 mm in the *y*-direction at a pump power of 330 W. The diameter of the cavity mode size was ~0.4 mm on mirror M2.

The seeder was a *Q*-switched Nd:YVO_4 oscillator with a wavelength of 1064 nm. The output power of the TEM_{00} seeder laser, which operated under a different frequency, is shown in figure 3. The maximum average power of the seeder laser was 6 W, 5 ns, 30 kHz at a pump current of 30 A. A horizontal cylindrical lens HCL1 ($F_{HCL1} = 250$ mm) and two vertical cylindrical lenses VCL1 ($F_{VCL1} = 150$ mm) and VCL2 ($F_{VCL2} = 100$ mm) were used to transform the output beam of the oscillator. HCL1 was used to focus the seeder

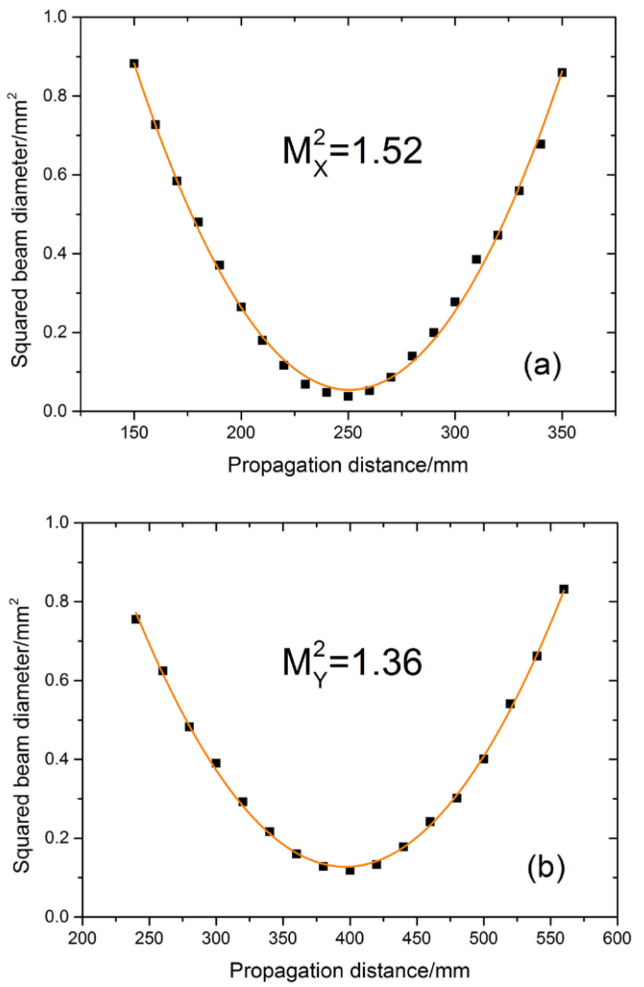

Figure 7. The beam quality in (a) the unstable direction and (b) the stable direction.

beam in the x-direction. VCL1 and VCL2 were configured as an anti-telescope system, resulting in a 3:2 collimation of the seeder beam in the y-direction. The cylindrical lenses HCL1, VCL1 and VCL2 were coated for HT at 1064 nm. M4 was a 45° flat mirror and was coated for HR at 1064 nm. The beam waist radius of the shaped seeder beam at the entrance of the amplifier (mirror M3) was 0.4 mm × 0.2 mm, as shown in figure 4. With $X_0 \approx 4.5$ mm and $m = 4$, the eight-pass Nd:YVO_4 slab amplifier was formed. Using equations (2) and (3), the output beam size in the x-direction was $W_4 = 1.67$ mm and $X_0 M^m - X_0 + W_0 + W_0 M^m = 16.4 \leqslant 18$ mm. The total length of the beam covering the pump line was approximately $b' \approx 16.9$ mm, which approached the crystal width 18 mm, and nearly all the pump area could be used.

Figure 5 shows the amplifier output power at different frequencies. Figure 6 shows the amplifier output power with different even numbers passing through the crystal at 30KHz. The maximum average output power was 77 W with an incident pump power of 330 W at 30 kHz. Taking into consideration 88% coupling efficiency and 95% absorbing efficiency, the optical-to-optical efficiency was 27.9%.

To measure the beam quality, a spherical lens with a focal length of 350 mm and a CCD were used. As the M^2 was defined by [11], $d_{(z)}^2 = d_0^2\left(1 + \left(\frac{4M^2\lambda z}{\pi d_0^2}\right)^2\right)$, where d_0 is the beam diameter of beam waist, z is the distance to the beam waist, $d(z)$ is the beam diameter at a distance z from the beam waist, and λ is the wavelength of the laser. The squared beam diameters at different positions in both directions at an output power of 77 W were obtained with the CCD, and fitted as shown in figure 7. The beam quality M^2 factors in the unstable and stable directions were 1.52 and 1.36, respectively.

4. Conclusion

In summary, we demonstrated a compact, efficient eight-pass Nd:YVO_4 slab laser amplifier based on a hybrid resonator. We obtained a maximum output power of 77 W at 30 KHz, with an optical-to-optical efficiency of 27.9%. The beam quality factors M^2 in the unstable and stable directions were 1.52 and 1.36, respectively.

Acknowledgments

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