Double-end-pumped $Nd:YVO_4$ slab laser at 1064 nm

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We demonstrate a high-power laser diode stacks double-end-pumped $Nd:YVO_4$ 1064 nm slab laser with a folded stable-unstable hybrid resonator. An output power of 220 W was obtained at the pump power of 490 W with optical conversion efficiency of 44.9%. At the output power of 202 W, the M^2 factors in the unstable direction and in the stable direction were 1.7 and 2.3, respectively. © 2012 Optical Society of America

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1. Introduction

Combining the high overlapping efficiency with outstanding cooling effect, partially end-pumped slab lasers with a stable—unstable hybrid resonator have been proved to be a proper method for power scaling with high beam quality and high efficiency [1–4]. In 2004, Shi *et al.* gained 110 W output using $Nd:YVO_4$ crystal with near-diffraction-limited beam quality [3]. Thin disc lasers allow high efficiency, but their pump shaping system are usually very complicated and to get good beam quality, the cavity lengths are very long [5,6].

Among various pump schemes, the end-pump configuration is very common for the laser diode pumped solid-state lasers, but the output power is usually limited to tens of watts because of serious thermal aberrations and thermally induced fracture of laser crystals [7,8]. For double-end-pump configurations, under the same pump power, the thermal gradient is smaller and the thermal focal length is longer compared with single-end-pump ones [9]. So double-end-pump configuration is adopted for higher power pump and can get higher output power. To this day, quite a few double-end-pump studies have been done [10–13] and the increase of output power was apparent.

In this research, we present a double-end-pumped $Nd:YVO_4$ slab laser with a stable—unstable hybrid resonator. An output power of 220 W laser was achieved under the pump power of 490 W; the M^2 were 1.7 in the unstable direction and 2.3 in the stable direction at the output power of 202 W. To the best of our knowledge, it is the highest output power for a laser diode end-pumped $Nd:YVO_4$ laser with a single laser crystal in the cavity.

2. Experimental Setup and Results

The experimental setup is shown in Fig. 1. The $Nd:YVO_4$ crystal, which has a 0.3 at.% Nd-ion concentration, was $14\ \mathrm{mm} \times 12\ \mathrm{mm} \times 1\ \mathrm{mm}$ in dimension. The a-cut laser crystal, which is close to M1, was wrapped with indium foil and mounted in a water-cooled heat sink with two large faces ($14\ \mathrm{mm} \times 12\ \mathrm{mm}$). The c axis was along the 14 mm direction. The two end faces ($14\ \mathrm{mm} \times 1\ \mathrm{mm}$) were both polished and high-transmission (HT) coated at 1064 nm and 808 nm. As displayed in Fig. 1, the main structure was made up of two laser-diode stacks, two coupling systems, and a folded cavity. Each of the two laser-diode stacks, which were fixed

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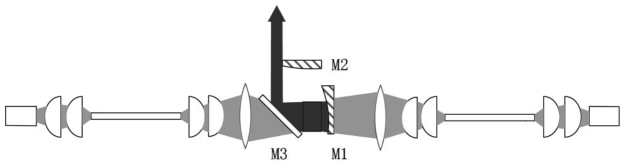

Fig. 1. Scheme of the experiment arrangement in the research.

on two water-cooled heat sinks, had four bars with central wavelength around 808 nm. Each bar was collimated by a cylindrical microlens individually in the vertical direction. The heat sinks of the two laser diodes and that of the crystal were all cooled by circulating water at the same temperature of 20 °C. Each coupling system consisted of four cylindrical lenses, a planar waveguide, and a group of spherical lens. Through the coupling systems, the pumping light was delivered into the laser medium and shaped rectangular on the each end of the slab crystal. The rectangular cross section had the dimensions of 14 mm × 0.4 mm, where 14 mm was the length in horizontal direction and 0.4 mm was the width in the vertical direction. The transfer efficiency of the pump systems was about 90%. Between the two coupling systems was the folded stable-unstable hybrid resonator. The resonator consisted of mirror M1, mirror M2, and mirror M3. M1 was a 500 cm radius of curvature concave spherical mirror with high reflection (HR) coated at 1064 nm and high transmission (HT) coated at 808 nm. M2 was a −350 cm radius of curvature convex cylindrical mirror with HR coated at 1064 nm. M3 was a flat mirror with 45° HR coated at 1064 nm and HT coated at 808 nm. The folded resonator was an off-axis positive confocal unstable resonator in the horizontal direction and a concave-flat stable resonator in the vertical direction. The cavity was 75 mm in length. The laser was coupled out at the edge of M2, which was polished. The magnification in the horizontal direction was $M = -R1/R2$ and the equivalent transmission was determined by the equation $T = 1 - 1/M = 30\%$.

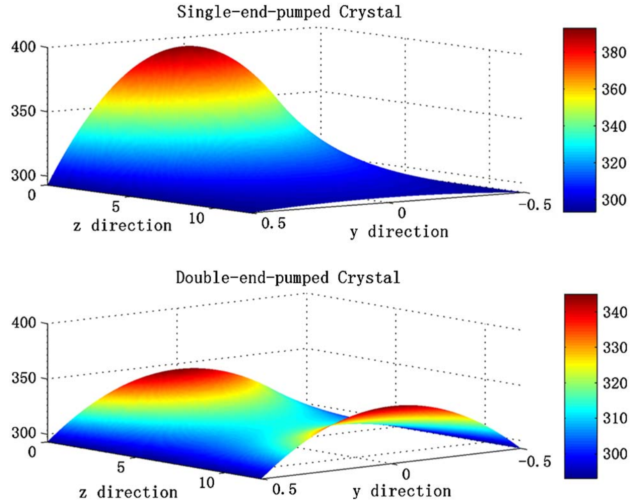

Fig. 3. (Color online) The temperature distributions of two pumped schemes; the y direction is the stable (vertical) direction and the z direction is the unstable (horizontal) direction.

Figure 2 shows the output power as a function of the pump power. With respect to the power emitted by the laser diode stacks, we achieved output power of 220 W at the pump power of 490 W with optical conversion efficiency of 44.9%. Taking the efficiency of the two coupling systems (~90%) into account, we achieved an output power of 220 W at the pump power behind the coupling systems of 441 W with optical conversion efficiency of up to 49.9%.

In comparison with the single-end-pumped scheme, we calculated the temperature distributions of the two schemes, which were under the same total pump power of 440 W, though the fracture of single-end-pumped $Nd:YVO_4$ crystal probably had occurred before the pump power got to 440 W [14]. As displayed in Fig. 3, the double-end-pump scheme had the smaller temperature difference of about 55 °C at each pump end of the crystal and the single-end-pumped scheme had a temperature difference of about 100 °C at the pump end. The double-end-pumped scheme decreased the temperature gradient

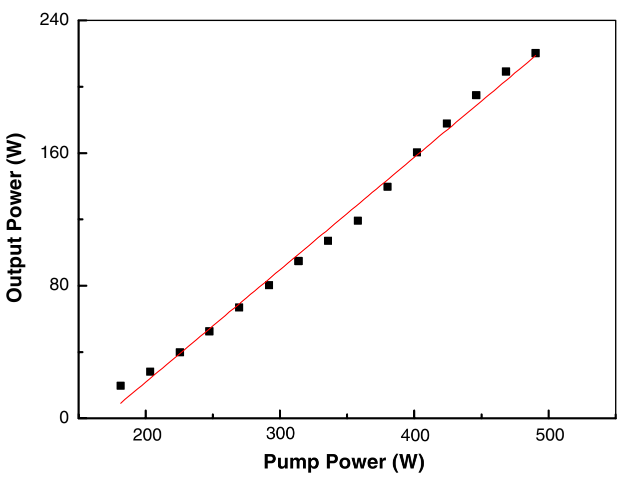

Fig. 2. (Color online) A plot of the output power as a function of the pump power.

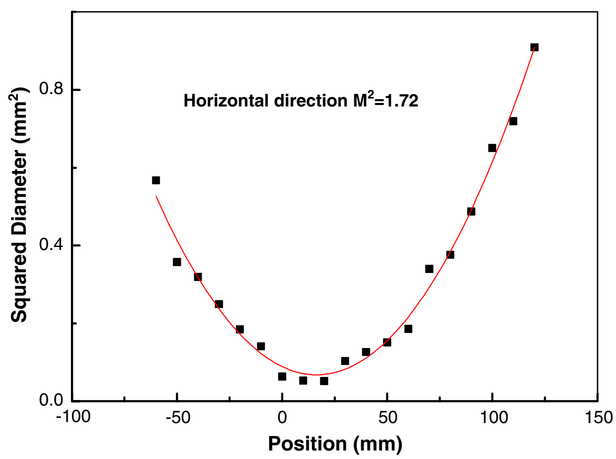

Fig. 4. (Color online) The widths of the beam profile at different positions in the unstable direction (horizontal direction) and the fitting result.

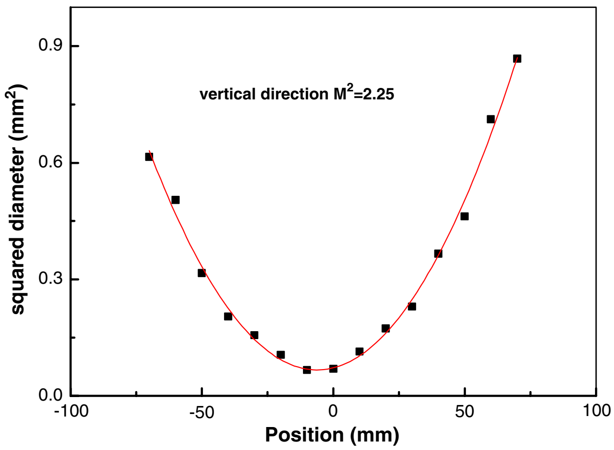

Fig. 5. (Color online) The widths of the beam profile at different positions in the stable direction (vertical direction) and the fitting result.

obviously. The better thermal effects decreased the thermal stress and also extended the stable region in the stable direction of the cavity to higher pump power. As a result, the double-end-pumped scheme was preferred to generate higher power laser output under higher pump power.

The M^2 factors were measured following the International Organization for Standardization method. We measured the M^2 factors at the output power of 202 W. We used a CCD camera (model: Beamon IR1310d, Israel) to measure the laser spot widths at different positions behind an $f = 400$ mm lens. The M^2 is defined by the formula:

$$d(z)^2 = d_0^2(1 + (4\lambda M^2 z/(\pi d_0^2))^2), \qquad (1)$$

where $d(z)$ is the diameter of beam at z position, d_0 is the diameter of beam at laser waist position, λ is the wavelength of laser, and z is the distance to the laser waist position. According to the formula, the squared beam diameters at different positions were fitted and the results are shown in Figs. 4 and 5. The M^2 factors were 1.7 and 2.3 in the unstable direction and in the stable direction, respectively.

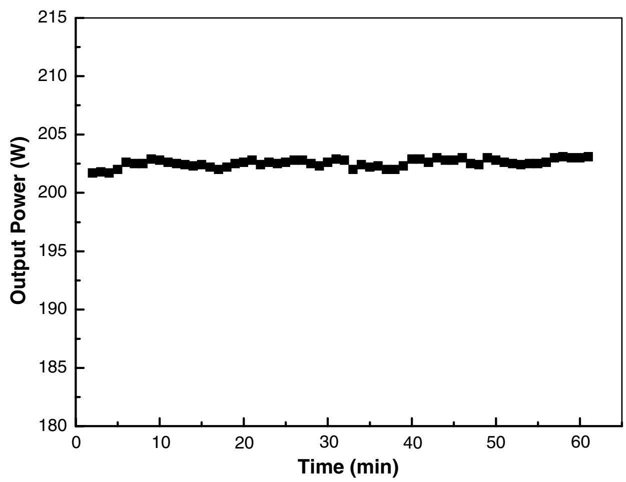

Fig. 6. The time stability test during one hour; the output power was recorded every minute.

We also monitored the time stability at the output power of 202 W for one hour and it is shown in Fig. 6. We recorded the power every minute and the time stability was about 0.3%.

3. Conclusion

In summary, we have demonstrated a double-end-pumped Nd:YVO_4 1064 nm slab laser with a stable-unstable hybrid resonator. We gained output power of 220 W at the pump power of 490 W emitted by the laser-diode stacks with optical conversion efficiency of up to 44.9%. At the output power of 202 W, the M^2 factors in the unstable direction in the stable direction were 1.7 and 2.3, respectively.

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