Near-diffraction-limited, 35.4 W laser-diode end-pumped Nd:YVO_4 slab laser operating at 1342 nm

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A diode stack end-pumped Nd:YVO_4 slab laser at 1342 nm with near-diffraction-limited beam quality by using a hybrid resonator was presented. At a pump power of 139.5 W, laser power of 35.4 W was obtained with a conversion efficiency of 25.4% of the laser diode to laser output. The beam quality M^2 factors were measured to be 1.2 in the unstable direction and 1.3 in the stable direction at the output power of 29 W.

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Laser emission around 1.3 μm has great applications in fiber communication, medical treatment, and laser radar. It also can be used to generate red and blue lasers by nonlinear frequency conversion and as the pumping source for a special laser, such as Co:MgF_2.

Nd^{3+}-doped gain media, such as Nd:YVO_4 [1–4], Nd:$GdVO_4$ [5,6], Nd:YAP [7], Nd:$LuVO_4$ [8], and Nd:YAG [9], were considered to be common laser gain medium to generate 1.3 μm radiation in laser-diode (LD)-pumped rod lasers, and much research had been done to achieve high output power. Although output power of more than 100 W was generated [7,9] by LD side-pumped solid-state lasers, generally speaking, its efficiency and beam quality were not as good as those of end-pumped lasers. Nd:YVO_4 has strong absorption at 808 nm in a rather broad bandwidth, a large emission cross section, and limited thermally induced beam aberration. In 2003, Di Lieto *et al.* [1] presented a 1342 nm laser with output power of 7.3 W by a single crystal and 12 W power output by twin Nd:YVO_4 crystal configuration. One year later, Minassian *et al.* [2] demonstrated a 13.7 W grazing-incidence Nd:YVO_4 slab laser with a diode-edge-pumped structure. In the same year, Yao *et al.* [3] obtained 11 W output at 1342 nm with a slope efficiency of 31.4% with a double-end-pumped Nd:YVO_4 rod laser. In 2008, Lu *et al.* [4] got 16.4 W output at 1342 nm by using two double-end-pumped Nd:YVO_4 rod crystals, and the beam quality was measured to be 1.7 and 1.9 in horizontal and vertical directions at an output power of 12 W. Nd:$GdVO_4$ was also a favorite gain medium in 1342 nm lasers owing to its good thermal conduction. Recently, Zhou *et al.* [6] achieved a 26.3 W cw by an LD end-pumped Nd:$GdVO_4$ rod laser with beam quality $M^2=30$ at the output power of 24 W. To the best of our knowledge, so far this is the highest power generated by LD end-pumped 1.3 μm solid-state lasers.

LD end-pumped slab lasers with hybrid resonators were proved to be a promising approach to generate laser with both high power and high beam quality [10,11]. However, by now most of the research work was focused on the emission line of ${}^4F_{3/2}\rightarrow{}^4I_{11/2}$ for Nd^{3+}-doped crystals. Recently, we adopted a positive-branch hybrid resonator to obtain a 1342 nm laser at pumping power of 100 W; the highest output power of 20.2 W was achieved with a slope efficiency of 26.3%, and M^2 factors were 1.2 in the unstable direction and 2.3 in the stable direction at an output power of 16 W [12]. To further improve the output

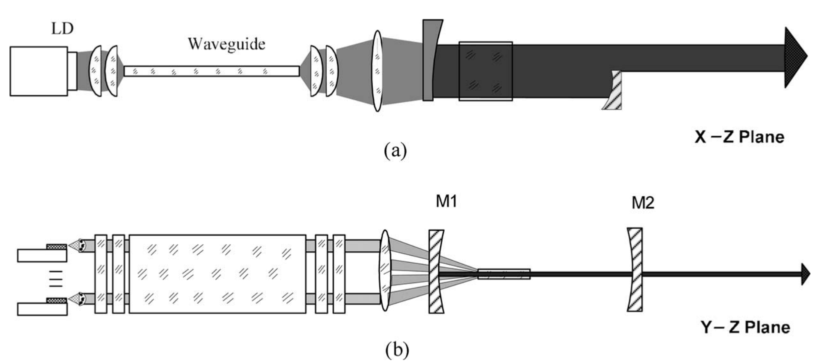

Fig. 1. Experimental setup of LD end-pumped Nd:YVO_4 slab laser with hybrid resonator in the (a) horizontal and (b) vertical directions.

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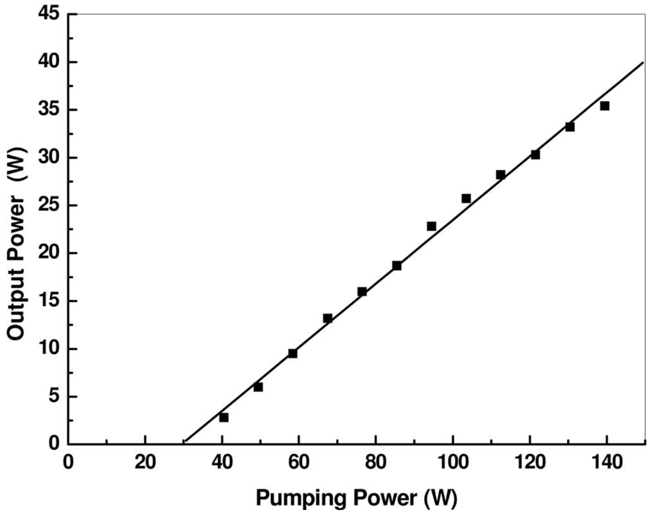

Fig. 2. Output power as a function of LD pump power.

power and beam quality, a negative branch with a longer cavity length was designed in this Letter. A 35.4 W output laser was created with a slope efficiency of 33.3%; beam quality M^2 factors were 1.2 in the unstable direction and 1.3 in the stable direction at an output power of 29 W.

Figure 1 is the schematic diagram of an LD end-pumped Nd:YVO_4 slab laser. The central wavelength of the LD was 808.6 nm, and the emission from each diode laser bar was individually collimated by microlens. A 12 mm × 0.4 mm homogeneous pumping line was generated inside the Nd:YVO_4 slab. The Nd:YVO_4 laser crystal with the size of 12 mm × 10 mm × 1 mm was 0.3 at. % doped and mounted between two water-cooled heats sinks with two large faces (12 mm × 10 mm). Indium foil was used for effective and uniform thermal contact and cooling. Both the LD stacks and the laser crystal were temperature controlled by circulating water. Line-shaped pumping line and efficient heat removal through two large faces induced a quasi-one-dimensional temperature gradient along the y axis.

As shown in Fig. 1, mirrors M1 and M2 built up an off-axis negative-branch confocal unstable resonator in the x–z plane and a thermal-induced stable resonator in the y–z plane. The resonator mirrors (M1, M2) were two concave spherical mirrors, with radii of 450 mm and 400 mm respectively, both of which were coated for high reflection (HR) at 1342 nm and high transmission (HT) at 808 nm and 1064 nm. M2 was cut and polished at one edge where the laser beam was coupled out. The magnification of unstable direction was $M = R1/R2 = 1.125$, and the outcoupling was $T = 1-(1/M) = 11\%$. Considering the insertion of the Nd:YVO_4 crystal in the resonator, the cavity length was adjusted to about 430 mm. In the unstable direction, an automatically collimated output beam was coupled out from the edge of M2 with a beam width of ~1.3 mm. While in the stable direction, there was a rather small Fresnel number $N \approx 0.44$ ($N = a^2/\lambda L$, $a = 0.5$ mm was the half-thickness of the slab and $L = 425$ mm was the cavity length), which induced a typically single TEM_{00} mode operating. Here, the thermal lens of gain medium was ignored.

The output power as a function of LD pumping power is shown in Fig. 2. When the pumping power was 139.5 W, the maximum output power of 35.4 W was achieved with slope efficiency of 33.3% and optical-to-optical efficiency of 25.4%. Taking the efficiency of the couple system (~88%) into account, the slope efficiency and the optical-to-optical efficiency would be 37.8% and 28.8%, respectively.

To measure the beam quality, a lens with focal length of 350 mm and a thin knife were used to get the beam diameters at different positions along the propagation. Using the M^2 factor, the propagation of the high-order laser beam can be described as $d(z)^2 = d_0{}^2[1+(4M^2\lambda z/\pi d_0{}^2)^2]$, [13], where d_0 is the diameter of beam waist, $d(z)$ is the beam diameter at the point z, λ is the wavelength, and z is the distance to the beam waist. The squared beam diameters in unstable and stable directions at an output power of 29 W were tested and fitted as shown in Fig. 3; the beam quality M^2 factors were 1.2 in the unstable direction and 1.3 in the stable direction, respectively. As we know, a side lobe does exist in the far field as a result of diffraction at output coupling mirror [13,14], and its intensity has been measured to be lower than

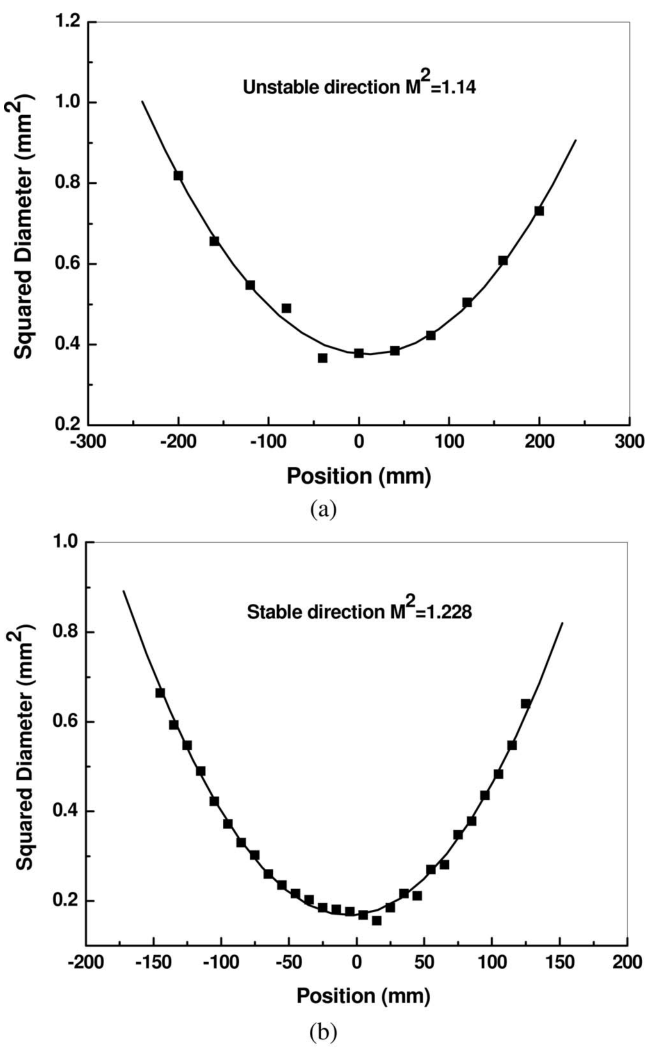

Fig. 3. Beam-quality measurements at output power of 29 W: (a) unstable direction, (b) stable direction.

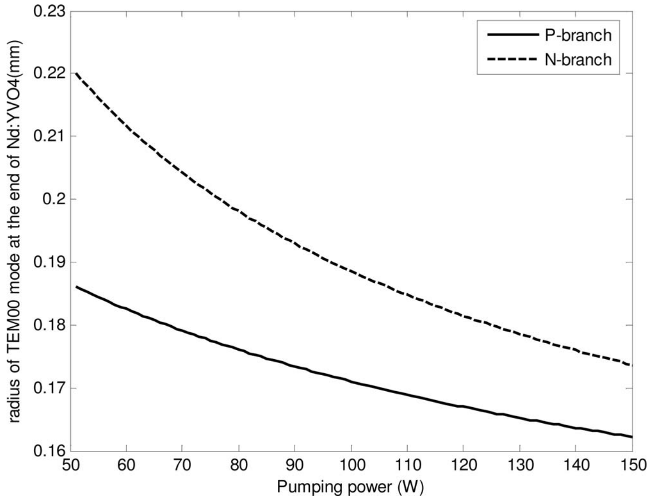

Fig. 4. TEM_{00}-mode beam radius in the stable direction as a function of pumping power.

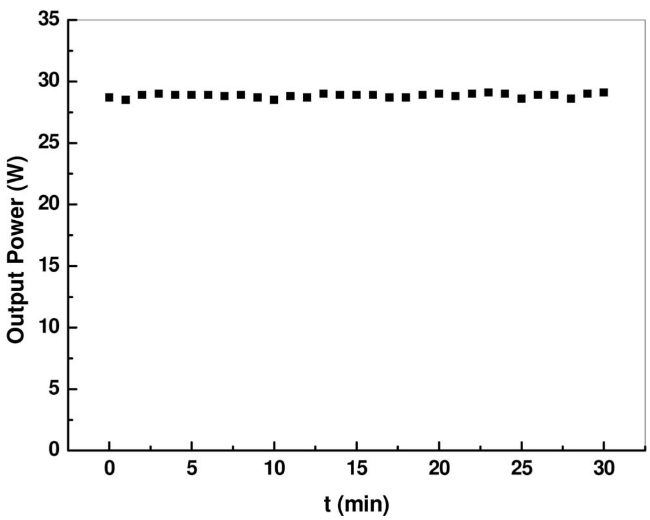

Fig. 5. Time stability of an LD end-pumped $Nd:YVO_4$ slab laser.

10% of peak value. Thus it is not included in beam diameters of Gaussian profile ($1/e^2 = 13.5\%$), and its influence on the testing results of beam size and M^2 factor can be neglected.

Compared with positive-branch hybrid resonator, both the efficiency and beam quality were increased in this experiment. It was mainly because the cavity length in positive-branch hybrid resonator was much shorter [$L = (R1 + R2)/2 = 25$ mm], and the Fresnel number was as large as ~7.5. The beam radiuses of TEM_{00} mode at the end of slab in stable direction are calculated in Fig. 4. From the figure, it could be seen that as the pumping power changed from 50 W to 150 W, the TEM_{00} mode of negative-branch resonator had a larger beam radius and better overlap with the pumping volume than the positive-branch resonator.

A significant astigmatism was also shown in Fig. 3. It was because that the almost-square laser beam at the output mirror was divergent in the stable direction and automatically collimated in the unstable direction. So an off-axis cylindrical telescoped system would be designed to adjust the beam waist in the unstable direction the same size as that in the stable direction.

We measured the stability of the LD end-pumped slab laser at an output power of 29 W for 30 min, and the results are shown in Fig. 5. No obvious fluctuations were observed. The stability was about 0.6%.

In conclusion, 35.4 W cw 1342 nm laser was generated with the pumping power of 139.5 W; the slope efficiency and optical-to-optical efficiency were 33.3% and 25.4%, respectively. At the output power of 29 W, the beam quality M^2 factors were measured to be 1.2 in the unstable direction and 1.3 in the stable direction, and the stability was about 0.6%.

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