High power diode-pumped 914-nm Nd:YVO_4 laser

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A high power continuous-wave (CW) 914-nm Nd:YVO_4 laser at room temperature is presented. Using an end-pumped structure and employing an 808-nm diode-laser as the pump source, the maximum output power of 15.5 W of the 914-nm laser is achieved at the absorbed pump power of 40.2 W, with a corresponding average slope efficiency η_s = 65.6%. To the best of our knowledge, this is the highest output power of diode-pumped 914-nm laser. A beam quality factor M^2 = 2.8 at the output power of 15 W is measured by using the traveling knife-edge method.

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High power compact all-solid-state lasers radiating in the infrared spectral regions around 900 nm have attracted much attention, because the blue lasers can be generated efficiently by frequency-doubling technology. Blue lasers have many important applications such as high-density optical data storage, biological and medical diagnostics, color displays, and underwater imaging or underwater communication[1]. Single polarization 914-nm laser oscillation can be realized between the transition of $^4F_{3/2}-^4I_{9/2}$ in Nd:YVO_4 for its uni-axial crystal structure, which is convenient for the frequency conversion in quasi-phase matching devices[2]. Additionally, high power laser emission at 914 nm with good beam quality can be also used as an efficient pump source for Yb-doped materials to obtain laser emissions around 980 nm[3].

In recent years, some works on diode-pumped continuous-wave (CW) and pulsed 914-nm Nd:YVO_4 and 457-nm deep blue lasers by intracavity frequency-doubling have been demonstrated[4−9]. For high power CW 914-nm laser, Zeller *et al.* reported 3.0-W 914-nm laser using diode-pumped composite Nd:YVO_4 crystal with an average slope efficiency η_s=22.8% and a beam quality factor M^2=2.9 at the maximum output power in 2000[4]. In 2002, at the incident pump power of 45 W, 5.8-W 914-nm laser with M^2=4.0 was presented by Gao *et al.* using a thin disk Nd:YVO_4 structure at a cooling fluid temperature of −35 °C[5]. In 2009, Gong *et al.* successfully scaled the output power of 914-nm laser to 7.3 W at the incident pump power of 29 W, corresponding to η_s=36%[6]. In 2009, our group reported that the maximum output power of 8.9 W at 914 nm was obtained at the incident pump power of 48.0 W, giving η_s=25.7%, and M^2=2.71 was estimated at the power level of 8.0 W[9]. As we know, it is a challenge to achieve high power high beam quality 914-nm laser output because of the nature of Nd^{3+}-doped quasi-three-level laser. Firstly, the stimulated-emission cross section of this transition is about 1/9 of the four-level $^4F_{3/2}-^4I_{11/2}$ transition generating 1064-nm laser. Secondly, the fact that the lower laser level is the upper 433-cm^{-1} crystal-field component of the $^4I_{9/2}$ ground-state manifold will result in significant reabsorption losses.

In this letter, we report a powerful diode-pumped 914-nm Nd:YVO_4 laser operating at roomtemperature. The maximum output power of 15.5 W of CW 914-nm laser is achieved at the absorbed pump power of 40.2 W, corresponding to η_s=65.6%. To our knowledge, this is the highest output power of 914-nm Nd:YVO_4 laser ever reported. By using traveling knife-edge method, M^2=2.8 is estimated at the output power of 15 W.

Figure 1 shows the experimental setup of the high power CW 914-nm laser. A fiber-coupled laser diode (LD) (HLU110F400, LIMO Inc., Germany) served as the pump source, which provided up to 110-W high brightness pump power from a fiber with a core diameter of 400 μm and a numerical aperture (NA) of 0.22. The pump beam was coupled into the gain medium by a coupling optical system, which consisted of two identical plano-convex lense with focal length of 21.3 mm. The pump beam was re-imaged into the laser crystals at

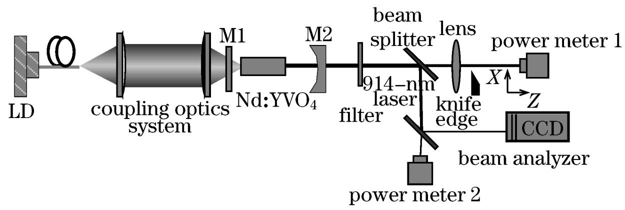

Fig. 1. Schematic of the experimental setup.

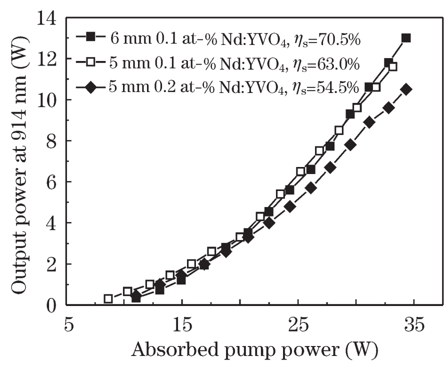

Fig. 2. Output power of 914-nm laser versus the absorbed pump power using different laser crystals.

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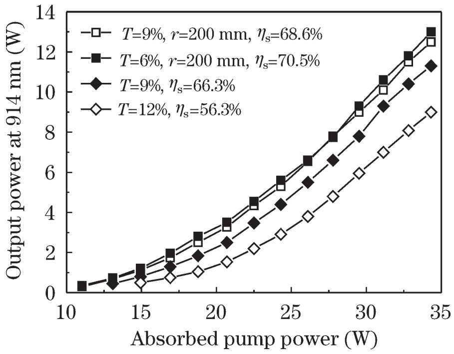

Fig. 3. Output power of 914-nm laser versus the absorbed pump power using different output coupling mirrors.

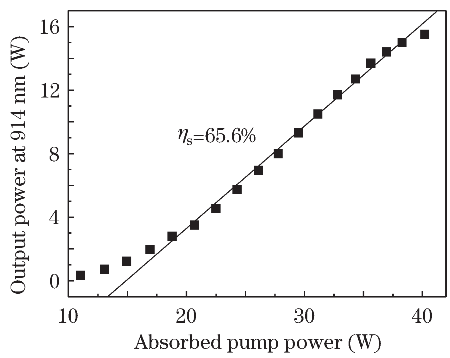

Fig. 4. Output power of 914-nm laser versus the absorbed pump power using the T=6%, r=200 mm output coupling mirror.

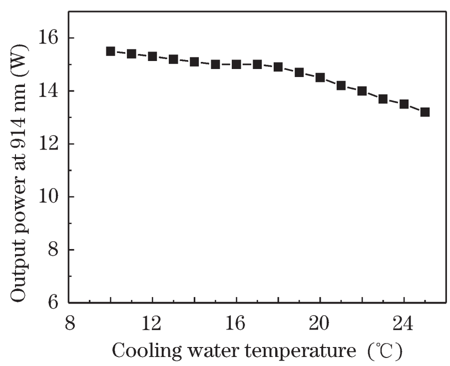

Fig. 5. Sensitivity of output power to the cooling water temperature at the absorbed pump power of 40.2 W.

a ratio of 1:1, and the coupling efficiency was 95%. The a-cut plane-parallel polished conventional Nd:YVO_4 rods were chosen as the gain medium. These rods are wrapped with 0.05-mm-thick indium foil, mounted in a copper micro-channel heat sink, and maintained at 10 °C by water cooling. The low operating temperature depopulated the higher lying Stark levels of the Nd^{3+}-ions on the ground state. To prevent the more efficient four-level transitions at 1064 and 1342 nm, both sides of the laser crystals were not only coated for high transmission (HT) at 914 nm ($T > 99.8\%$) and 808 nm ($T > 99\%$), but also antireflection (AR) coated at 1064 nm ($R < 2\%$) and 1342 nm ($R < 10\%$). The experiments were carried out with simple linear cavities with a cavity length of 25 mm, because the short cavity could reduce the influence of the thermal-lensing effect on the stability of the cavity. The plane input mirror M1 had AR coating at 808 nm and high-reflection (HR) coating at 914 nm ($R > 99.8\%$), M2 was highly transmitting at 1064 and 1342 nm and partially transmitting at 914 nm as an output mirror. The output power was recorded by laser power meters (PM30, Coherent Inc., USA) and the laser intensity distribution was displayed by a laser beam analyzer (LBA-712PC-D, Spiricon Inc., USA).

To realize high power 914-nm laser operation, firstly, oscillation of the four-level laser with higher stimulated-emission cross section should be restrained. Secondly, the influences resulting from the thermal-lensing effect, upconversion, the amplified spontaneous emission (ASE) effect, as well as the reabsorption loss effect need to be minimized. For the sake of solving these severe problems in the quasi-three-level transition, Nd^{3+}-doped concentration and length of the Nd:YVO_4 laser media should be optimized. In experiments, 0.1 and 0.2 at.-% doped level Nd:YVO_4 rods with the dimensions of 3×3×5 and 3×3×6 (mm) were used. In a plane-concave cavity with an output coupling mirror of T=6% at 914 nm and radius of curvature r=200 mm, three kinds of Nd:YVO_4 rods were used. With the Nd^{3+}-doped concentration of 0.1 at.-%, 5- and 6-mm-long laser rods are tested. Another kind of laser rod was doped with 0.2 at.-% Nd^{3+} concentration and 5 mm in length. Under the same condition, they had different absorption percents of the pump laser. For the laser rod with the Nd^{3+}-doped concentration of 0.1 at.-%, 5-mm length, the absorption percent was ∼55%, and the absorption percents for the 0.1 at.-%, 6-mm rod and 0.1 at.-%, 6-mm rod were ∼60%. To compare the output laser performance equally, we recorded the laser output power at the same absorbed pump power. 914-nm laser operating results are shown in Fig. 2. At the lower pump power stage, nonlinear increase of the output power for 914-nm laser is found; however, the laser operates like a four-level system and the output power increases linearly and efficiently at higher pump power. For the 5-mm 0.1 at.-% laser rod, the lasing threshold is the lowest and the laser output power is the highest at the beginning stage. But with the pump power increasing, the laser output power for 6-mm 0.1 at.-% rod exceeds those of the other two kinds of rods, and 13.0-W 914-nm laser can be achieved at the absorbed pump power of 34.3 W, furthermore, η_s=70.5% is estimated at the linear increasing region, which is also higher than those of the other two kinds of rods. Especially, 0.2 at.-% Nd^{3+}-doped laser crystal is not favorable for high power 914-nm laser operation, because the rod may rupture for majority of the pump light is absorbed locally. The inhomogeneous absorption will limit the scaling of the pump power in the end-pumped structure. For high power 914-nm laser operation, the 6-mm 0.1 at.-% crystal will be used.

Further tests were conducted to estimate the best output coupling mirror for high power 914-nm laser operation. In the experiments, two kinds of concave mirrors (T=9%, r=200 mm and T=6%, r=200 mm) and two kinds of plane mirrors (T=9% and T=12%) were used, and the 914-nm laser performance was recorded. As shown in Fig. 3, for the T=6%, r=200 mm output mirror, the lasing threshold is the lowest, and the laser output power is the highest at the same pump power. Using the other three kinds of mirrors, the maximum output power of 12.5 W (T=9%, r=200 mm), 11.3 W (T=9%), and

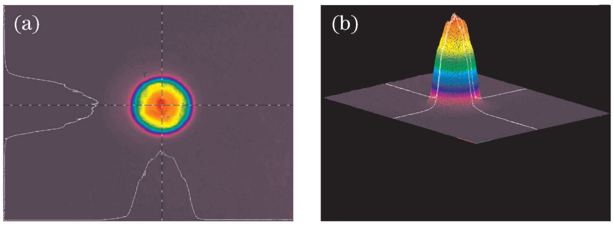

Fig. 6. Profile of the 15-W 914-nm laser beam.

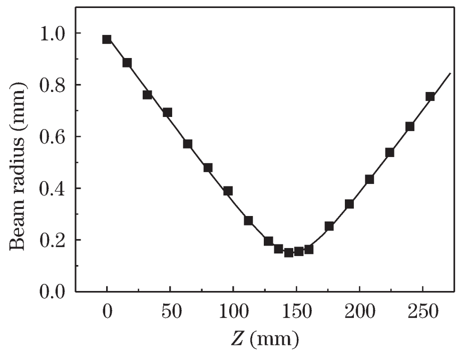

Fig. 7. Beam radius for 15-W 914-nm laser as a function of the distance from the focusing lens. Solid curve is a fitting curve to a standard Gaussian beam propagation expression.

9.0 W (T=12%) were obtained at the absorbed pump power of 34.3 W, corresponding to η_s=68.6%, 66.3% and 56.3%. Then, the 914-nm laser outputs were not inclining to saturate.

Using the T=6%, r=200 mm output coupling mirror, a high power 914-nm Nd:YVO_4 laser operation was realized. Figure 4 presents that the maximum power of 15.5 W is achieved at the absorbed pump power of 40.2 W, with the corresponding optical-to-optical conversion efficiency η_{o-o}=38.6% and η_s=65.6%. Above the absorbed pump power of 37.0 W, the output power was inclining to saturate. Considering that 914-nm Nd:YVO_4 laser is a quasi-three-level laser system, the ground-state reabsorption will affect the laser output power. Reducing the cooling water temperature will reduce the absolute temperature in the laser rod and depress the ground-state reabsorption to a certain extent. The sensitivity of output power to the cooling water temperature at the absorbed pump power of 40.2 W is described in Fig. 5. The thermal sediment is very serious in the laser medium in the high pump field, and the focal length of thermal lensing will be much shorter. We found that at the high absorbed pump power of 40.2 W, the output power would fall down evidently when the cavity length was longer than 45 mm.

The typical beam profile for 914-nm laser at the output power level of 15.0 W was measured with the laser beam analyzer at about 30-mm distance from the output coupling mirror. Two-dimensional (2D) and three-dimensional (3D) far-field intensity distributions for the laser beam are shown in Fig. 6. The beam radius for 914-nm laser at 15.0-W output power was also measured by the traveling 90/10 knife-edge method. Figure 7 shows the measured beam radius at different distances from the lens. By fitting Gaussian beam standard expression to these data, the beam quality was estimated to be M^2=2.8.

In conclusion, we demonstrate a high power 914-nm Nd:YVO_4 laser by using an 808-nm diode-end-pumped structure. At the absorbed pump power of 40.2 W, up to 15.5-W CW 914-nm laser is obtained, corresponding to η_{o-o}=38.6% and η_s=65.6%. Also, the beam quality factor at the output power of 15 W is measured to be M^2=2.8 using the traveling knife-edge method.

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