Compact, efficient diode-end-pumped Nd:$GdVO_4$ slab continuous-wave 912-nm laser

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A fiber-coupled laser-diode (LD) end-pumped Nd:$GdVO_4$ slab continuous-wave (CW) 912-nm laser and an LD bar end-pumped Nd:$GdVO_4$ slab CW 912-nm laser are both demonstrated in this paper. Using the fiber-coupled LD of end-pumped type, a highest CW 912-nm laser output power of 10.17 W is obtained with a high optical–to–optical conversion efficiency of 24.6% and a slope efficiency of 34.5%. The measured M^2 factors of beam quality in x and y directions are 5.3 and 5.1, respectively. Besides, an LD bar of end-pumped type is used to realize CW 912-nm laser output, which has the advantages of compactness and low cost. When the pump power is 38.8 W, the output power is 8.87 W and the measured M^2 factors of beam quality in x and y directions are 16 and 1.31, respectively. In order to improve the beam quality of the 912-nm laser at x direction, a new quasi-concentric laser resonator will be designed, and an LD bar end-pumped Nd:$GdVO_4$ slab high-power CW 912-nm TEM_{00} laser will be realized in the future.

Keywords: diode-end-pumped, Nd:$GdVO_4$ slab, LD bar, 912-nm laser

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1. Introduction

Since Fan and Byer[1] reported the first diode-pumped Nd:YAG 946-nm laser at room temperature in 1987, much attention has been paid to lasers emitting around 0.9 μm in the past few years.[2−15] These lasers have some unique applications such as in water–vapor lidars and differential absorption lidars for ozone measurements or remote sensing, they can also be used as the pump source for Yb-doped crystals and Yb-doped fibers.[2−5] Diode-pumped Nd^{3+}-doped quasi-three-level lasers have also attracted much attention for generating blue lasers by frequency-doubled technology.[15−17] The blue lasers have applications in the fields of biological and medical diagnostics, underwater imaging and communication, high-density optical storage, and colour displays.[15] Recently, quasi-three-level lasers emitting around 0.9 μm have been demonstrated for Nd:YAG, Nd:YVO_4, and Nd:$GdVO_4$ crystals.[2,3,5,14] Compared with the other two kinds of laser materials, Nd:$GdVO_4$ crystals have a higher absorption coefficient and a larger absorption cross section at 808 nm.[6] The thermal properties of Nd:$GdVO_4$ crystals such as low thermal expansion coefficient and large specific heat are better than those of Nd:YVO_4 crystals.[6] Among the three kinds of laser materials, Nd:$GdVO_4$ crystals have the largest thermal conductivity.[6]

In recent years, much progress has been made in laser-diode (LD) end-pumped all-solid-state 0.9-μm-lasers. In 2006, Zhou *et al.*[5] reported 15.2-W continuous-wave (CW) 946-nm laser output with a slope efficiency of 45%, using an LD end-pumped type and employing a diffusion bonded Nd:YAG rod.[5] In 2010, Yu *et al.* presented a high power LD end-pumped Nd:YVO_4 CW 914-nm laser with the highest output power of 15.5 W and a corresponding average slope efficiency of 65.6%.[14] In 2009, Liu *et al.* demonstrated quasi-three-level 912-nm CW laser emission under direct diode laser pumping at 880 nm into emitting level $^4F_{5/2}$ of Nd:$GdVO_4$. A highest output power of 8.1 W was obtained with a slope efficiency of 67.9%.[6] In 2010, Chen *et al.* reported a 16.2-W CW 912-nm laser output with an average slope efficiency of 41.7% and an optical–to–optical conversion efficiency of 24.2%, using an LD end-pumped structure.[3]

In the LD end-pumped all-solid-state 0.9-μm lasers, the pump sources are all-fiber-coupled laser diodes. However, as is well known, using the fiber coupled LD end-pumped type usually makes the laser compact, inexpensive, and low-thermal-loaded, which can limit power scaling, laser system efficiency and

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output beam quality. In order to overcome these problems, an LD bar directly end-pumped type is employed in our experiment, which has the properties of both the high overlap efficiency of fiber-coupled LD end-pumped rod lasers and the excellent cooling conductivity of LD bar end-pumped slab lasers. Furthermore, an Nd:$GdVO_4$ slab chosen in our experiment has a strong polarized absorption characteristic, which meets the polarized output property of the LD bar. All of these make the LD bar directly end-pumped Nd:$GdVO_4$ slab 912-nm laser feasible and realizable.

In this paper, an efficient fiber-coupled LD end-pumped Nd:$GdVO_4$ slab CW 912-nm laser and an LD bar end-pumped Nd:$GdVO_4$ slab CW 912-nm laser are both presented in detail. First, we demonstrate an efficient fiber-coupled LD end-pumped Nd:$GdVO_4$ slab CW 912-nm laser. Second, we use an LD bar as the pump source and an LD bar directly end-pumped Nd:$GdVO_4$ slab CW 912-nm laser is successfully operated. A highest output power of 8.87 W is gained with an optical–to–optical conversion efficiency of 22.9%. To the best of our knowledge, the CW output power of 912-nm laser gained by LD bar end-pumped type is the highest.

2. Fiber-coupled LD end-pumped Nd:$GdVO_4$ slab CW 912-nm laser

2.1. Experimental setup

A fiber-coupled LD end-pumped Nd:$GdVO_4$ slab CW laser operating at 912 nm is first studied. A simple linear two-mirror cavity configuration used is shown in Fig. 1. The cavity length is 15 mm. A high-brightness 45-W 808-nm fiber-coupled diode laser with a fiber core diameter of 400 μm and a numerical aperture of 0.22 is employed. A multi-lens optical coupler with a 20-mm focal length and 95% coupling efficiency is used to re-image the pump beam onto the gain medium with a spot size of about 250 μm in diameter. The gain medium is a plano-parallel polished Nd:$GdVO_4$ crystal with 0.15 at-% Nd^{3+} doping level. The size of the Nd:$GdVO_4$ crystal is 6 mm×10 mm×2 mm. The pump and output facets of the Nd:$GdVO_4$ crystal are both coated with a high transmission coating at 912-nm ($T > 99\%$) laser. The Nd:$GdVO_4$ crystal closely wrapped by a piece of indium is set in a heat sink made of the red copper. Considering that 912-nm Nd:$GdVO_4$ 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 slab and depress the ground-state reabsorption to some extent. Therefore, the temperature of the slab is kept at 13 °C which is the minimum value of the adjustable temperature of the water cooler. The temperature of the pump source maintains 25 °C by water cooling. Considering that the strong laser oscillations at 1063 nm and 1340 nm must be suppressed, special films at two mirrors are coated. The input mirror (M1) is a planar mirror with a high reflection coating at 912 nm ($R > 99\%$) and high transmission coatings at 808 nm ($T > 95\%$), 1063 nm ($T > 90\%$), 1340 nm ($T > 98\%$). The output coupler (M2) is also a planar mirror with a partial transmission coating at 912 nm ($T = 7.6\%$), high transmission coatings at 1063 nm ($T > 95\%$) and 1340 nm ($T > 96\%$).

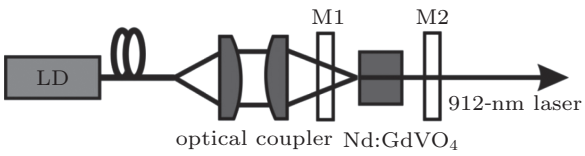


Fig. 1. Experimental setup of a fiber-coupled LD end-pumped Nd:$GdVO_4$ slab CW 912-nm laser.

2.2. Experimental results

The curve for the output power versus the pump power is shown in Fig. 2. The threshold pump power is 11.7 W. When the pump power is increased to 41.3 W, the output power goes up to 10.17 W with a slope efficiency of 34.5% and an optical–to–optical conversion efficiency of 24.6%. As is seen from Fig. 2, the output power is not saturated with the increase of the pump power. If we continue increasing the pump power, it is possible to obtain a higher output power and conversion efficiency. During the experiment, the lasing lines at 1063 nm and 1340 nm are all observed to be successfully suppressed. Figure 3(a) shows the spectrum from 900 nm to 1100 nm at an output power of 10.17 W. The corresponding spectral line width of the 912-nm laser is 0.28 nm, which is shown in Fig. 3(b). When the output power is 10.17 W, the measured M^2 factors of beam quality as measured by a beam propagation analyzer (Spiricon M^2-200S) in x and y directions are 5.3 and 5.1, respectively, the corresponding beam propagation behaviour is shown in Fig. 4(a). Since a short linear cavity is employed, the laser operates with a multi-mode output at high pump powers.

The far-field output beam profile is shown in Fig. 4(b), which retains a symmetrical shape well.

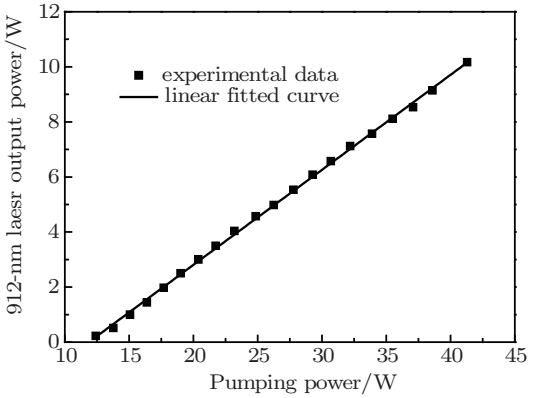


Fig. 2. Output power of the CW 912-nm laser versus pump power.

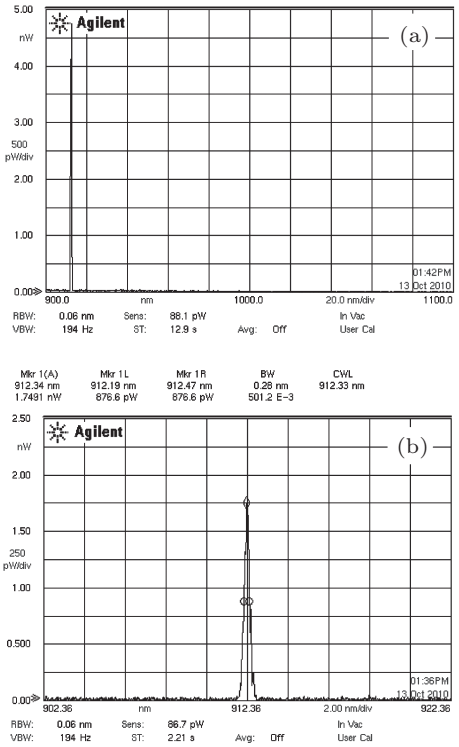


Fig. 3. (a) Spectrum from 900 nm to 1100 nm at an output power of 10.17 W, (b) spectrum of 912-nm laser line.

Next, a plano-concave mirror with a curvature radius of 50 mm is used as the output mirror, which is coated with partial transmission at 912 nm ($T = 4.8\%$) and high transmission coatings at 1063 nm ($T > 95\%$), and 1340 nm ($T > 95\%$). The other experimental conditions are not changed. The experimental results are similar to those obtained above. The relation between the CW 912-nm laser output power and pump power is shown in Fig. 5. The highest output power obtained is 9.93 W with a slope efficiency of 27% and an optical–to–optical conversion efficiency of 24%. The transmission at 912 nm of the plano–concave mirror is lower than that of the planar mirror and therefore, the threshold pump power is decreased to 5.6 W. Because the plano–concave cavity is more stable than the plano–plano cavity, its 912-nm laser output power is not easily affected by small disturbances. When the pump power is 41.3 W, the short-term instability of the output power is measured and the result is shown in Fig. 6. We record the output power every minute using a calibrated thermal power meter head from OPHIR NOVA II, and in a time period of fifteen

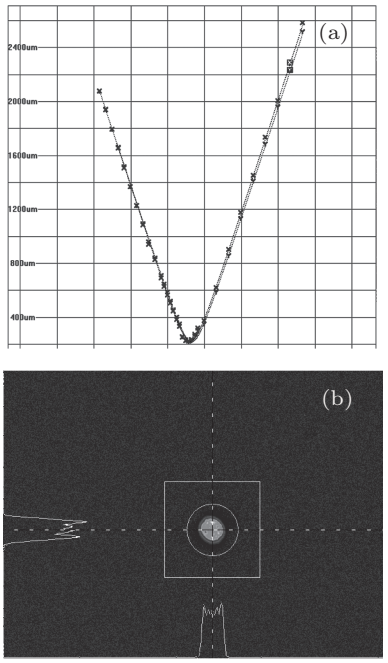


Fig. 4. (a) Propagation behaviour of the output beam at an output power of 10.17 W, (b) far-field output beam profile.

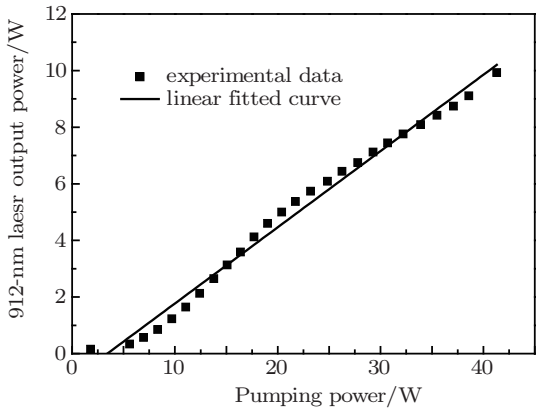


Fig. 5. Output power of the CW 912-nm laser versus pump power.

minutes, the instability of the output power can be obtained from the following formula:

$$\Delta P/\overline{P} = \sqrt{\frac{\sum_{i=1}^{n}\left(P_i - \overline{P}\right)^2}{n-1}} \cdot \frac{1}{\overline{P}} \approx 0.16\% \quad (n = 15), \quad (1)$$

where n is defined as the number of samples. The measured result indicates that the output power of the CW 912-nm laser is very stable.

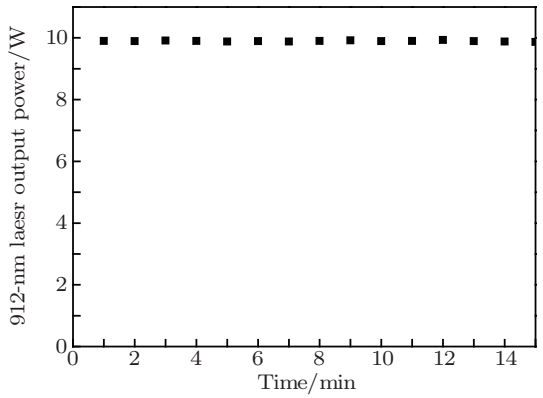


Fig. 6. Short-term instability of the 912-nm laser output power at a pump power of 41.3 W.

3. LD bar end-pumped Nd:$GdVO_4$ slab CW 912-nm laser

3.1. Experimental setup

Next, an LD bar end-pumped Nd:$GdVO_4$ CW laser emitting at 912 nm is studied. A simple linear two-mirror cavity is also used, which is shown in Fig. 7. The Nd:$GdVO_4$ slab and two planar mirrors are the same ones used in the above experiment. The cavity length is 18 mm. An LD bar with a maximum 808-nm output power of 50 W is used in the experiment. The light-emitting area of the LD bar is 10 mm×0.7 mm with a certain angle of divergence. An optical coupler system with a coupling efficiency of 70% is employed to shape the pump light. The spot size of the pump light on the incident face of the Nd:$GdVO_4$ crystal is about 1.5 mm×0.2 mm.

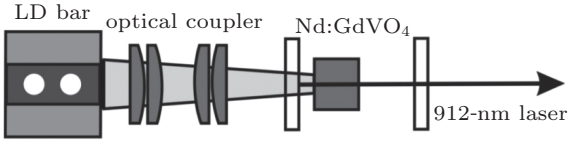


Fig. 7. Experimental setup of an LD bar end-pumped Nd:$GdVO_4$ slab CW 912-nm laser.

3.2. Experimental results

The curve of the CW 912-nm laser output power as a function of the pump power is shown in Fig. 8. As is shown in Fig. 8, a highest output power of 8.87 W is achieved when the pump power is 38.8 W, with a slope efficiency of 32.8% and an optical–to–optical conversion efficiency of 22.9%. The threshold pump power is 8.87 W. The output power is not saturated with increasing pump power and therefore, it can be deduced that once an LD bar with

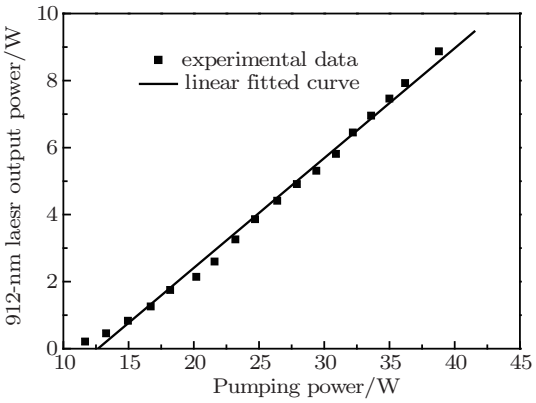


Fig. 8. Output power of the CW 912-nm laser versus pump power.

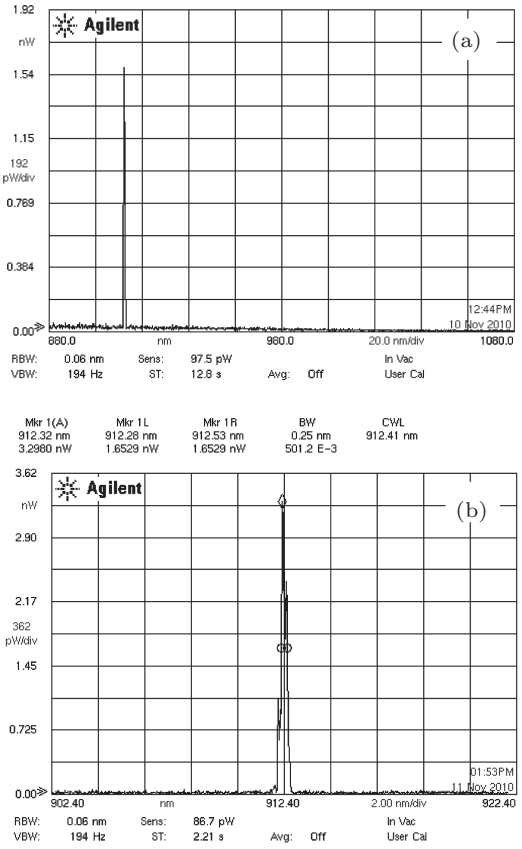


Fig. 9. (a) Spectrum from 900 nm to 1100 nm at an output power of 8.87 W, (b) spectrum of 912-nm laser line.

a higher 808-nm output power is used, the 912-nm output power will be enhanced greatly. Figure 9(a) shows the spectrum from 900 nm to 1100 nm at an output power of 8.87 W and the strong oscillations at 1063-nm and 1340-nm lasers are both suppressed successfully. The line width of the 912-nm laser is 0.25 nm, which is shown in Fig. 9(b). When the output power is 8.87 W, the measured M^2 factors of beam quality in x and y directions are 16 and 1.31, respectively. The corresponding beam propagation behavior and far-field output beam profile are shown in Fig. 10. Due to the severe mismatch between the sizes of the pump light and the 912-nm laser fundamental mode on the laser crystal in the x direction, the beam quality of the output 912-nm laser in the x direction is very poor. In order to improve this beam quality, a new quasi-concentric laser resonator with line-shaped end-pumping profile will be used to solve the problem of mode mismatch.[18] An efficient, compact LD bar end-pumped Nd:$GdVO_4$ CW 912-nm laser with a higher output power and a better output beam quality can be expected.

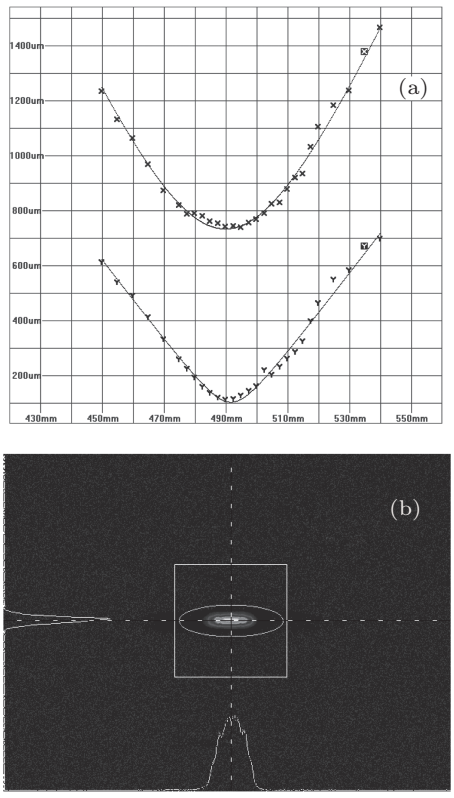


Fig. 10. (a) Propagation behavior of the output beam at an output power of 8.87 W, (b) far-field output beam profile.

4. Conclusions

In summary, a fiber-coupled LD end-pumped Nd:$GdVO_4$ slab CW 912-nm laser and an LD bar end-pumped Nd:$GdVO_4$ slab CW 912-nm laser are both demonstrated. By using the fiber-coupled LDend-pumped type, a highest CW 912-nm laser output power of 10.17 W is obtained with a high optical–to–optical conversion efficiency of 24.6% and a slope efficiency of 34.5%. The measured M^2 factors of beam quality in x and y directions are 5.3 and 5.1, respectively, and the corresponding far-field output beam profile remains symmetrical. When the laser cavity is changed into a planar–concave resonator, a highest CW 912-nm laser output power of 9.93 W is obtained with a high optical–to–optical conversion efficiency of 24% and a slope efficiency of 27%. The short-term instability of the 912-nm laser output power at a pump power of 41.3 W is better than 0.16%. Besides, an LD bar end-pumped type is used to realize CW 912-nm laser output, which has the advantages of compactness, low cost, high thermal loading, and weak thermal effect. When the pump power is 38.8 W, the output power is 8.87 W. The measured M^2 factors of beam quality in x and y directions are 16 and 1.31, respectively and the far-field output beam profile shows an elliptic shape, which results from the severe mode mismatch.

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