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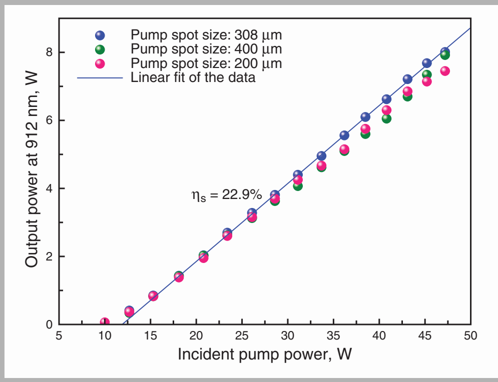
Abstract: High efficiency operation on continuous-wave (cw) 912 nm laser at room temperature in Nd:GdVO$_4$ crystal pumped by 808 nm diode-laser is reported in this letter. The maximum output power of 8.0 W was obtained at the incident un-polarized pump power of 47.0 W, giving the corresponding optical-to-optical conversion efficiency of 17.0% and the average slope efficiency of 22.9%. Further tests show that the lasing threshold is reduced and the efficiency is increased evidently when using the π-polarized 808 nm pump source. 4.8 W 912 nm laser was achieved at the polarized pump power of 21.8 W, optical-to-optical conversion efficiency is increased to 22.0% and average slope efficiency is up to 33.6%.



Output powers of the 912 nm laser with three different couplers

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Diode-laser-pumped high efficiency continuous-wave operation at 912 nm laser in Nd:GdVO$_4$ crystal

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1. Introduction

The diode-pumped quasi-three-level Nd^{3+}-doped laser, which operates on the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition, has attracted much attention in the past few years [1–3]. This is because the laser around 900 nm has some unique applications such as water vapor lidars and differential absorption lidars (DIALs) for ozone measurements, and it also can be used as the pump source for the Yb-doped crystals and Yb-doped fibers. Moreover, high power blue laser will be achieved efficiently by means of frequency doubling to the laser around 900 nm, which has a large number of applications ranging from high-density optical data storage, biological and medical diagnostics, color displays to underwater imaging and communication.

Many works have been done in diode-pumped Nd:GdVO$_4$ lasers [4–13], especially, 912 nm laser has been demonstrated by J. Gao and X. Yu et al. [14,15] that 8.6 W and 3.65 W 912 nm laser were achieved pumped by 808 nm and 879 nm diode-laser, respectively. By frequency converter technology, 456 nm deep blue laser also has been reported that output power of 5.3 W in cw operation by F. Jia et al. in 2006 [16] and peak power of 315 W at 10 kHz with pulse duration of 140 ns by J. Gao et al. in 2008 [17]. It can be concluded that Nd:GdVO$_4$ crystal has been expected to be a highly performed laser medium, this is partially due to its large absorption cross-section near 808 nm and stimulated emission cross-section at 912 nm. In addition, Nd:GdVO$_4$ is especially more suitable for the operation of quasi-three-level laser according to its high thermal conductivity, which is very important because, first of all, it leads to a smaller temperature gradient and therefore to a smaller thermal lens, secondly it decrease the absolute temperature in the laser crystal, so the

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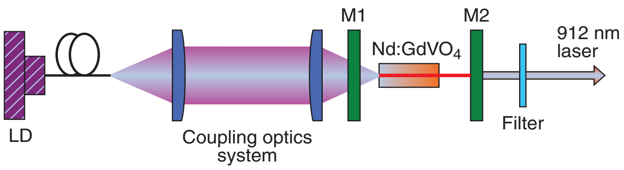

Figure 1 (online color at www.lphys.org) Schematic of the experimental setup

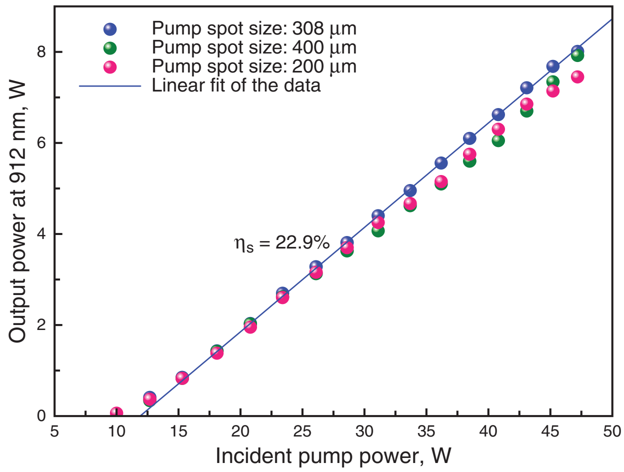

Figure 2 (online color at www.lphys.org) Output powers of the 912 nm laser with three different couplers

reabsorption losses due to the thermal population of the lower laser level (409 cm^{-1}) are reduced. Furthermore, an uni-axial crystal structure of Nd:GdVO$_4$ is convenient for the laser oscillation with single polarization, which is good for the frequency conversion in quasi-phase matching devices. However, there were few reports on high efficiency cw 912 nm laser source with good beam quality.

In this paper, a high efficiency, high beam quality, compact, continuous-wave 912 nm laser is developed based on fiber coupled 808 nm diode-laser pumping. With an incident pump power of 47.0 W, 8.0 W output power for 912 nm laser is achieved. The optical-to-optical conversion efficiency and the average slope efficiency are 17.0% and 22.9%, respectively. A beam quality factor M^2 is 2.98 at the output power of 8.0 W measured by the traveling 90/10 knife-edge method [18]. At the polarized incident pump power of 21.8 W, 4.8 W 912 nm laser was achieved, optical-to-optical conversion efficiency is increased to 22.0% and average slope efficiency is up to 33.6%.

2. Experimental setup

Fig. 1 is a sketch of the experimental setup. A linear resonator is employed to make the system very simple and compact. The total length of the resonator is 25 mm. The pump source used in our experiment is a high brightness fiber-coupled LD from Advanced Photonic Systems, which delivers a maximum output power of 50 W at 808 nm from the end of a fiber with 400 μm core in diameter and a N.A. of 0.22. The pump beam is coupled into the gain medium by the coupling optics, which consists of two plano-convex lenses with the coupling efficiency of 94%. The gain medium is a plane-parallel polished a-cut Nd:GdVO$_4$ grown by the Czochralski method, with the Nd^{3+} doping level of 0.2 at.% and the dimensions of 3×3×5 mm^3. Low doped and long laser crystal is favorable to reduce thermal lens and the reabsorption loss of quasi-three-level system, while guaranteeing adequate absorption efficiency for the pump light. The crystal is wrapped with 0.05 mm thick indium foil, mounted in a copper micro-channel heat sink and maintained at 13±0.1°C by water cooling. Both sides of the laser crystal are coated for high transmission (HT) at 912 nm ($T > 99.8\%$) and the 808 nm ($T > 99\%$). Antireflection coating (AR) at 1063 nm ($R < 2\%$) and 1340 nm ($R < 10\%$) is considered to prevent these more efficient four-level transitions. The simple plano-plano or plano-concave cavities are used in the experiment. The plane input mirror M1 has AR coating at the 808 nm ($R < 10\%$) and high-reflection (HR) coating at 912 nm ($R > 99.8\%$), the M2 are highly transmitting at 1063 nm and 1340 nm, and is partially transmitted at 912 nm as an output mirror. The laser spectrum is measured by a fiber spectrometer (American. Ocean Optics Inc. HR4000) and the output power is recorded by a laser power meter PM30 (American. Coherent Inc).

3. Results and discussion

In principle, the lasing threshold of 912 nm laser in Nd:GdVO$_4$ that is end-pumped by a fiber-coupled diode and edge cooled is given by Eq. (1) [1]:

$$P_{th} = \frac{\pi h\nu_p(\omega_l^2 + \bar{\omega}_p^2)\left[T + (L + 2\sigma_e f_1 N^0 l)\right]}{4\sigma_e \tau (f_1 + f_2)\eta_a}\,, \tag{1}$$

where $h\nu_p$ is the energy of a pump photon, $\bar{\omega}_p$ and ω_l are the radius of the pump beam and the laser mode, respectively, σ_e is the stimulated emission cross section, N^0 is the concentration of doping ions, f_1 and f_2 are the fractional populations of the lower and the upper laser levels, respectively, τ is the fluorescence decay time, T is the transmission for 912 nm laser of the output coupled mirror, $(L + 2\sigma_e f_1 N^0 l)$ represents the total loss consisting of the passive cavity loss L and the reabsorption loss $2\sigma_e f_1 N^0 l$. η_a is the pump quantum efficiency and l is the length of Nd:GdVO$_4$ crystal. To reduce the lasing threshold and increase the optical efficiency, therefore, high absorption efficiency for the pump radiation is necessary at a certain

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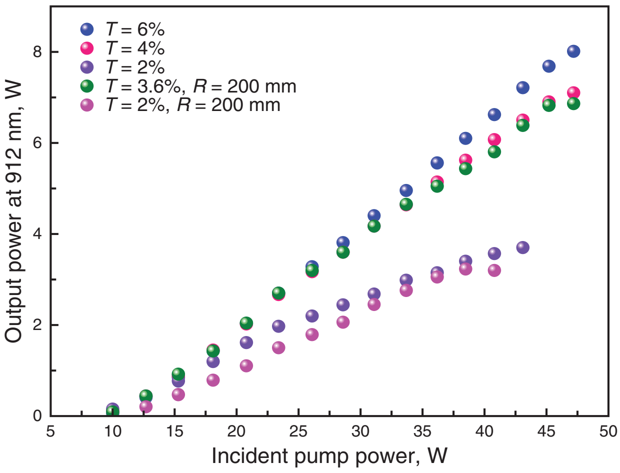

Figure 3 (online color at www.lphys.org) Output powers of the 912 nm laser with different output mirrors

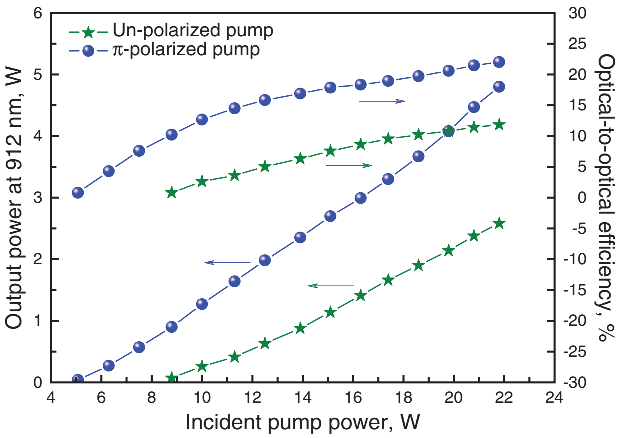

Figure 4 (online color at www.lphys.org) Output powers and optical-to-optical efficiency of the 912 nm laser versus the incident pump power of the π-polarized 808 nm laser and the unpolarized

length and Nd^{3+}-doped concentration for the $Nd:GdVO_4$ crystal.

To overcome the shortcoming of the low stimulated-emission cross-section in the $^4I_{9/2} \rightarrow {}^4F_{3/2}$ transition and to improve the output power of 912 nm laser, the pump beam should be focused to a small spot in the gain medium. Strong beam focusing, however, will result in severe thermal-lensing effect, which maybe leads to the instability of the cavity, thus pump spot size should be optimized in high pump power field. Fig. 2 shows the output powers of the 912 nm laser in a plano-plano cavity (Length of the cavity is 25 mm, transmission ratio of output mirror at 912 nm is $T = 6\%$) with three different coupling optics, which result in spot sizes of 400, 308, and 200 μm, respectively. When the pump spot size is 308 μm, the highest output power of 8.0 W is achieved under the incident pump power of 47.0 W. The optical-to-optical conversion efficiency is 17.0%, and the average slope efficiency is up to 22.9%.

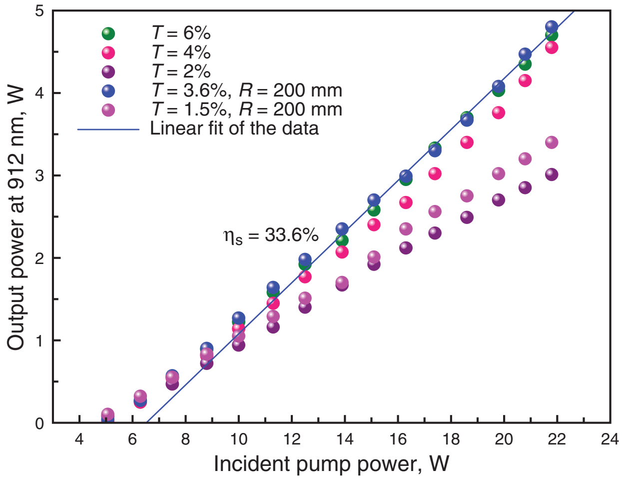

Figure 5 (online color at www.lphys.org) Output powers of the 912 nm laser with different output mirrors

Under the pump spot size of 308 μm, the output power for 912 nm laser was measured with five different output mirrors, including three kinds of plane output coupled mirrors with transmissions of $T = 6\%$, $T = 4\%$, $T = 2\%$, and two concave mirrors with the radius of curvature of 200 mm and transmissions of $T = 3.6\%$, $T = 1.5\%$. Using the output coupled mirrors of $T = 6\%$, $T = 4\%$, $T = 3.6\%$, a linear increase of the output power for 912 nm laser at the lower pump power is shown in Fig. 3, the laser threshold was measured to be 10 W, which is relatively too high is mainly because the lower laser level population, leads to a serious reabsorption loss at the beginning stage. Another reason is that the central wavelength of the LD isn't matching the absorption peak value of $Nd:GdVO_4$ very well in the lower pump power field. At the higher pump power, the laser operates like a four-level system, and the output power increases linearly and efficiently. Fig. 3 also presents that it is inclined to saturate for $T = 4\%$, $T = 3.6\%$ from the pump power of 45 W and $T = 2\%$, $T = 1.5\%$ from the power of 25 W. However, it isn't saturated for $T = 6\%$ at the highest pump power of 47.0 W, then maximum output power of 8.0 was achieved. The beam quality factor value of 8.0 W laser is measured to be $M^2 = 2.98$ by the traveling 90/10 knife-edge method, to our knowledge, which is the best at the similar power level for 912 nm laser.

$Nd:GdVO_4$ crystal has a stronger absorption efficiency to π-polarized 808 nm laser than the un-polarized and the σ-polarized [19]. According to Eq. (1), π-polarized 808 nm laser can be used as the pump source to increase the efficiency further. In experiments, we inserted a po-

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larized disk in the coupling optics system to generated π-polarized 808 nm diode laser, as it was described in [20]. Tests show that up to 82% of the polarized pump radiation is absorbed by the crystal. Fig. 4 gives a comparison for 912 nm laser in Nd:$GdVO_4$ pumped by the π-polarized 808 nm laser source and the un-polarized under the same conditions. The output coupler is a concave mirror of $T=3.6\%$. As results, the lasing threshold of Nd:$GdVO_4$ pumped by the two sources is 5.0 W and 8.8 W, respectively, and obviously the output power and optical-to-optical efficiency of the 912 nm laser using the π-polarized pump source will be much higher than that of using the un-polarized at the same incident pump power.

The output power for 912 nm laser was also measured at the pump spot size of 308 μm. Using the $T=6\%$, $T=4\%$, $T=3.6\%$ output coupled mirrors, Fig. 5 shows that a nonlinear increase of the output power for 912 nm laser at the lower pump power, this is because in the operation on quasi-three-level laser, the low circulating intensity exists in the cavity and the reabsorption loss affects the slope efficiency seriously. As the pump power increases, the intensity becomes higher so that it saturates the reabsorption loss, so the laser operates like a four-level system, and the output power increases linearly and efficiently at the high pump power. Maximum output power of 4.8 W was achieved using the concave output coupled mirror $T=3.6\%$ at the incident pump power of 21.8 W, corresponding to the optical-to-optical conversion efficiency is 22.0% and the average slope efficiency is 33.6%, moreover, the output power for 912 nm laser isn't saturated then.

4. Conclusion

In summary, we have demonstrated a highly efficient 912 nm Nd:$GdVO_4$ laser by using a 808 nm diode-end-pumped structure at room temperature. At the incident pump power of 47.0 W, up to 8.0 W continuous-wave 912 nm laser was obtained, with corresponding optical-to-optical efficiency is 17.0%, and the average slope efficiency is up to 22.9%. Also, the beam quality factor at the power of 8.0 W was measured to be $M^2=2.98$. Using the π-polarized 808 nm pump source can reduce the lasing threshold and increase the efficiency evidently. 4.8 W 912 nm laser was achieved at the polarized pump power of 21.8 W, optical-to-optical conversion efficiency is increased to 22.0% and average slope efficiency is up to 33.6%. Thus, in the future research, high power π-polarized 808 nm diode-laser will be employed to improve efficiency and the output power for 912 nm laser.

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