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Characteristics of $Nd:GdVO_4$ Laser with Different Nd-Doping Concentrations *

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We report the properties of a compact diode-pumped continuous-wave $Nd:GdVO_4$ laser with a linear cavity and different Nd-doped laser crystals. In a 0.2 at.% Nd-doped $Nd:GdVO_4$ laser, 1.54 W output laser power is achieved at 912 nm wavelength with a slope efficiency of 24.8% at an absorbed pump power of 9.4 W. With 0.3 at.% Nd-doping concentration, we can obtain the either single-wavelength emission at 1064 nm or 912 nm or the dual-wavelength emission at 1064 nm and 912 nm by controlling the incident pump power. From an incident pump power of 11.6 W, the 1064 nm emission between ${}^4F_{3/2}$ and ${}^4I_{11/2}$ is suppressed completely by the 912 nm emission between ${}^4F_{3/2}$ and ${}^4I_{9/2}$. We obtain 670 mW output of the 912 nm single-wavelength laser emission with a slope efficiency of 5.5% by taking an incident pump power of 18.4 W. Using a $Nd:GdVO_4$ laser with 0.4 at.% Nd-doping concentration, we obtain either the single-wavelength emission at 1064 nm or the dual-wavelength emission at both 1064 nm and 912 nm by increasing the incident pump power. We observe a strong competition process in the dual-wavelength laser.

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During the last few years, the diode-pumped cw lasers operating at the ${}^4F_{3/2}$–${}^4I_{9/2}$ transition emitting in the range of 900–950 nm for the neodymium ion have attracted much attention in many application areas because of their potential to generate high-power blue laser output through frequency doubling.[1−7] Most studies in this field have concentrated on Nd:YAG crystals. In order to obtain wavelengths in the deeper blue (below 460 nm), $Nd:YVO_4$ and $Nd:GdVO_4$ crystals can be used.[8,9] $Nd:YVO_4$ and $Nd:GdVO_4$ crystals have larger absorption coefficients at 808 nm compared to a Nd:YAG crystal. Moreover, the laser radiation of $Nd:YVO_4$ and $Nd:GdVO_4$ is linearly polarized, which is important for frequency doubling. The advantage of the $Nd:GdVO_4$ crystal compared to a $Nd:YVO_4$ crystal is the higher heat conduction in the $\langle 110\rangle$ direction which is comparable with that of a Nd:YAG crystal. We set up a compact diode-pumped cw $Nd:GdVO_4$ laser emitting at 912 nm with a linear cavity using the crystals with different Nd-doping concentrations. With a $Nd:GdVO_4$ laser using 0.2 at.% Nd-doping concentration, 1.54 W output power at 912 nm wavelength is achieved with a slope efficiency of 24.8% at an absorbed pump power of 9.4 W. Using a $Nd:GdVO_4$ laser with 0.3 at.% Nd-doping concentration, we can obtain either single-wavelength laser emission at 1064 nm or 912 nm, or dual-wavelength emission at 1064 nm and 912 nm by changing the incident pump power. When the incident pump power was 11.6 W, the 1064 nm emission which is emitted by a four level system is suppressed completely by the 912 nm emission which is emitted by a quasi-three level system. We obtain 670 mW output power at 912 nm with a slope efficiency of 5.5% at the incident pump power of 18.4 W. Using a $Nd:GdVO_4$ crystal with 0.4 at.% Nd-doping concentration, we obtain either the single-wavelength emission at 1064 nm or the dual-wavelength laser emission at 1064 nm and 912 nm by increasing the incident pump power. We observe a strong competition process in the dual-wavelength laser.

Figure 1 shows the experimental setup of the $Nd:GdVO_4$ laser. A linear resonator was employed to make the system simple and compact. We used a high-power LIMO HLU25F200 pump system with a fibre coupler (with the core diameter of 200 μm and NA=0.22) providing the output power up to 25 W. We used $Nd:GdVO_4$ crystals with 0.2 at.% Nd^{3+} concentration ($3\times 3\times 4$ mm), 0.3 at.% Nd^{3+} concentration ($3\times 3\times 3.6$ mm) and 0.4 at.% Nd^{3+} concentration ($3\times 3\times 3$ mm). The laser crystal was mounted in a water-cooled heat sink ($T = 10°$C). For simplicity and reduction of cavity loss, the pump facet of the $Nd:GdVO_4$ crystals was coated for high reflection (HR) at 912 nm, antireflection (AR) at 808 nm and high transmission (HT) at 1.06 μm and 1.34 μm. The other end of the laser crystals were AR coated at 1.06 μm, 1.34 μm and 912 nm. The output coupler has 3.6% transmission at 912 nm with 50 mm radius of curvature.

Figure 2 shows the output power at 912 nm laser

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versus the incident pump power of Nd:$GdVO_4$ with 0.2 at.% Nd-doping. Figure 2(a) depicts the result of the experimental setup described above. Figure 2(b) illustrates the experimental result after optimization of the cavity. We obtained 1.54 W output power at 912 nm laser with a slope efficiency of 14.4% at the incident pump power of 18.8 W and a slope efficiency of 24.8% for the absorbed pump power of 9.4 W. The absorbed pump power is only half the incident pump power. From Fig. 2, we can see that the output power at the maximum pump power was not saturated. Therefore, higher output power could be obtained by increasing the pump power. By the way, from the above-described experiment, we can see that the laser only operated at 912 nm single-wavelength when the Nd-doping concentration is 0.2 at%. This is probably because the reabsorption loss of the quasi-three level system is small in lower Nd-doping concentration, so that 912 nm laser could realize high-efficiency operation. Contrarily, in this lower Nd-doping concentration, the 1064 nm laser operating at the four-level system could not oscillate because the gain is smaller than the loss of the cavity. The far-field beam profile of the 912 nm laser at the output power of 1 W was measured and the result is shown in Fig. 3. A nearly Gaussian beam intensity profile was obtained. We observed the stability of the laser by monitoring the 912 nm output power with a power meter. The output noise was 0.7% (rms) in 30 min at the output power level of 1 W. The output power was very stable and no degradation was observed.

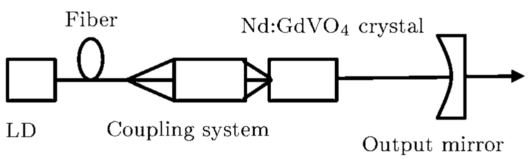

Fig. 1. Schematic diagram of the compact diode-pumped Nd:$GdVO_4$ laser.

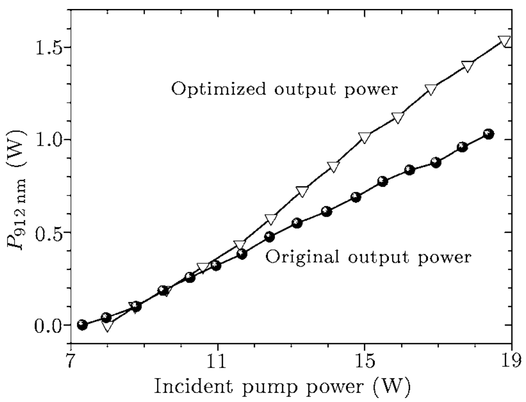

Fig. 2. The laser output power at 912 nm versus the incident pump power for a Nd:$GdVO_4$ crystal with 0.2 at.% Nd-doping concentration.

The result of the Nd:$GdVO_4$ laser with 0.3 at.% Nd-doping concentration is shown in Fig. 4. Figure 5 shows the spectra of 1064 nm and 912 nm laser emission that were measured using a high-resolution spectrometer. The threshold of the 1064 nm laser was 6.3 W (Fig. 5(a)). In the range from 6.3 W to 7.3 W, single-wavelength laser operation at 1064 nm was observed. The emission at 912 nm started at an incident pump power of 7.3 W (Fig. 5(b)). We observed dual-wavelength emission at 1064 nm and 912 nm when the incident pump power was in the range from 7.3 W to 11.6 W. When the incident pump power was 11.6 W, the 1064 nm laser emission was suppressed completely by 912 nm laser emission (Fig. 5(c)). The 912 nm laser emission increased gradually when the incident pump power exceeded its threshold of 7.3 W. We obtained 670 mW output power at 912 nm with a slope efficiency of 5.5% at the incident pump power of 18.4 W. We could explain the above experiment in this way. When the Nd-doping concentration increased to 0.3%, 1064 nm laser operating at the four-level system began to oscillate because the gain is just higher than the loss of the cavity, but the efficiency of 1064 nm laser is lower. For 912 nm laser, although the reabsorption loss increased with the increasing of Nd-doping concentration, 912 nm laser still could realize efficient operation. With the increasing incident pump power, 912 nm laser could suppress completely 1064 nm laser through the mode competition. However, from Fig. 4, we can see that the maximum output of 912 nm single-wavelength already decreased to 670 mW due to the reabsorption loss.

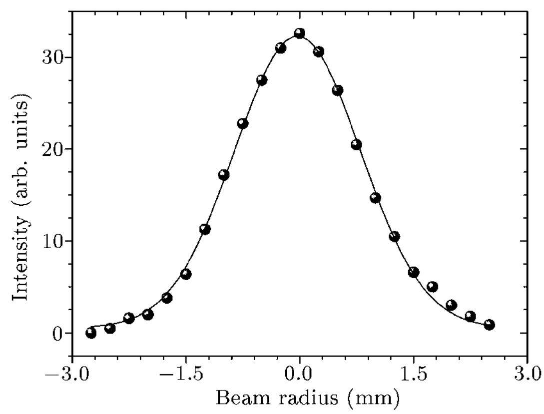

Fig. 3. The far-field beam profile of the 912 nm laser of the Nd:$GdVO_4$ laser with 0.2 at.% Nd-doping concentration.

Figure 6 shows the output power of the laser emission at 912 nm and 1064 nm versus the incident pump power using Nd:$GdVO_4$ laser with 0.4at.% Nd-doping. The threshold of 1064 nm laser emission was 8.2 W. We obtained single-wavelength laser emission at 1064 nm when the incident pump power was in the

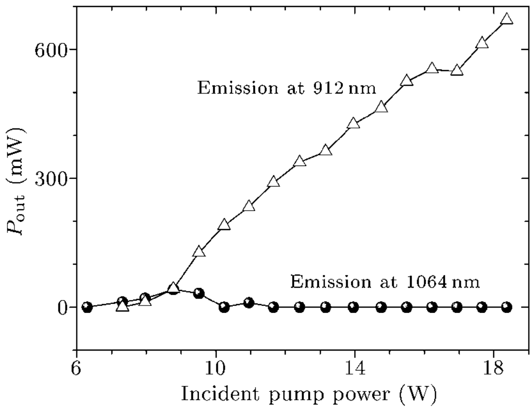

Fig. 4. The output power of 1064 nm and 912 nm laser of the Nd:$GdVO_4$ laser with 0.3 at.% Nd-doping concentration versus the incident pump power.

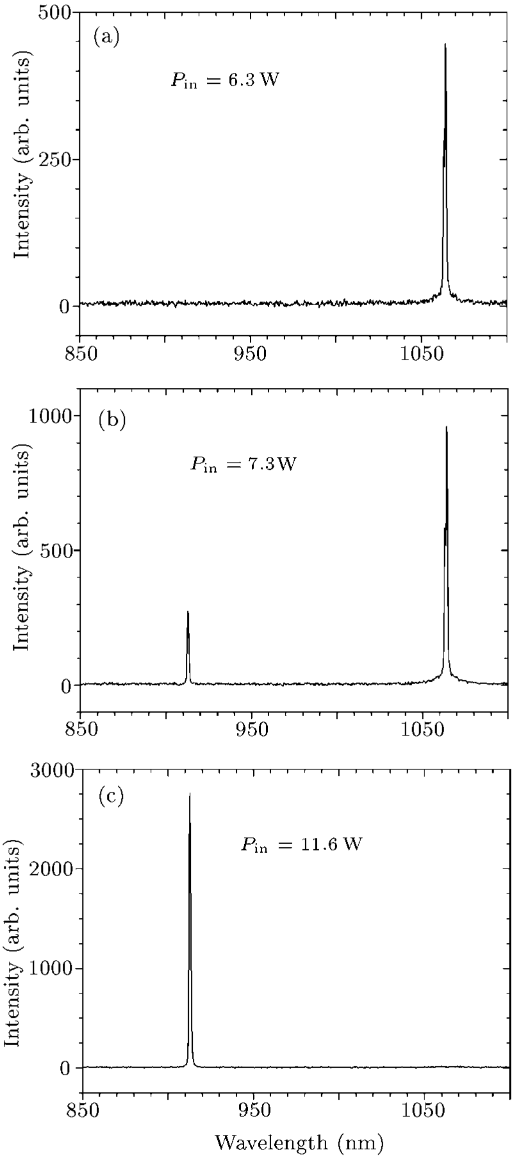

Fig. 5. The spectra of 1064 nm and 912 nm laser emission by increasing the incident pump power of the Nd:$GdVO_4$ laser with 0.3 at.% Nd-doping concentration.

range from 8.2 W to 9.9 W. The 912 nm laser emission started when the incident pump power was 9.9 W. We observed the competition process of the dual-wavelength laser emission at 1064 nm and 912 nm when the incident pump power was in the range from 9.9 W to 18.4 W. We obtained 400 mW (250 mW of 1064 nm laser and 150 mW 912 nm laser) total output power at 912 nm and 1064 nm laser emission with an optical conversion efficiency of 2.2% at the incident pump power of 18.4 W. We could understand the above experiment in this way. When the Nd-doping concentration further increased to 0.4%, 1064 nm laser could realize efficient operation because the gain increased. However, the reabsorption loss of 912 nm laser further increased in this Nd-doping concentration, the laser efficiency still decreased. Thus the mode competition between 912 nm and 1064 nm laser became stronger. In the competition process, we found that the relative output power of each wavelength was very sensitive to the alignment of the output mirror. This can mainly be explained by the alignment dependent relative cavity loss. Detailed theoretical analysis of the competition process of 1064 nm and 912 nm laser output is our next work. From the above experimental results of different Nd-doped Nd:$GdVO_4$ crystals, we can see that the mode competition between 912 nm and 1064 nm laser would become stronger with the increasing of Nd^{3+} concentration.

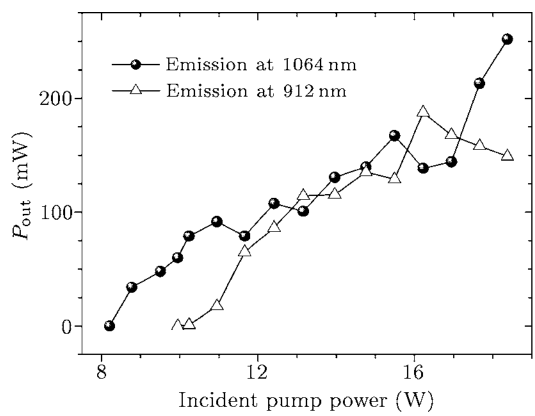

Fig. 6. The output power of the 1064 nm and the 912 nm laser emission versus the incident pump power of the Nd:$GdVO_4$ laser with 0.4 at.% Nd-doping concentration.

In conclusion, we have experimentally demonstrated the properties of a compact diode-pumped cw Nd:$GdVO_4$ laser with a linear cavity and different Nd-doped laser crystals. Using a Nd:$GdVO_4$ crystal with 0.2 at.% Nd-doping concentration, 1.54 W output power at 912 nm is achieved with a slope efficiency of 24.8% at an absorbed pump power of 9.4 W. With a doping concentration of 0.3 at.%, we could obtain either single-wavelength laser emission at 1064 nm or 912 nm, or dual-wavelength laser emission at 1064 nm and 912 nm by controlling the incident pump power. When the incident pump power is 11.6 W, the 1064 nm laser emission is suppressed completely by the 912 nm laser emission. We obtain 670 mW output power at 912 nm with a slope efficiency of 5.5% at the incident pump power of 18.4 W. Using 0.4 at.% doping concentration, we obtain either single-wavelength laser emission at 1064 nm or dual-wavelength laser emission at 1064 nm and 912 nm by increasing the incident pump power. We observe strong competition process in the dual-wavelength laser emission.

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