Experimental study of the generation of a blue laser by intracavity frequency doubling of a cw $Nd{:}GdVO_4$ laser with lithium borate

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Received 5 January 2009; revised 22 March 2009; accepted 15 April 2009; posted 20 April 2009 (Doc. ID 105965); published 20 May 2009

Efficient cw intracavity frequency doubling of a diode end-pumped $Nd{:}GdVO_4$ laser that operates in the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition at 912 nm is demonstrated. A 15 mm long lithium borate crystal, cut for critical type I phase matching at room temperature, was used for second harmonic generation of the fundamental laser. A maximum output power of 14.8 W in the deep blue spectral range at 456 nm was achieved at an incident pump power of 40 W. In 2 h we achieved an optical-to-optical conversion efficiency of 37% with a better than 2.57% power stability. © 2009 Optical Society of America

OCIS codes: 140.0140, 140.3580, 140.3480.

High-power blue light is necessary for many applications, such as optical data storage, communication, spectroscopy, large image projection, and the medical field. For such applications, a high-power blue light source must be compact, have a high optical-to-optical efficiency, and have a long reliable operational life. A diode-pumped solid-state blue laser is a promising way to achieve a blue light source. After Fan and Byer [1] first introduced a laser-diode-pumped quasi-three-level 946 nm Nd:YAG laser at room temperature in 1987, the 473 nm blue light produced by intracavity second harmonic generation was studied extensively [2–8]. To obtain a deeper blue spectrum region, such as below 460 nm, a$Nd{:}GdVO_4$ laser is a good candidate to achieve this goal. By use of a simple linear resonator we obtained a 30 mW, 456 nm laser with 190 mW at 912 nm. A Z cavity was used to achieve 840 mW output power at 456 nm with a slope efficiency of 16%. The corresponding 456 nm blue laser with an output power of 5.3 W is available commercially.

0003-6935/09/162979-04$15.00/0

Here we demonstrate a significant improvement in the generation of a high-power cw blue laser by frequency doubling inside a compact and efficient diode end-pumped $Nd{:}GdVO_4$ laser operated at 912 nm, yielding a 14.8 W deep blue laser at 456 nm with high beam quality. To the best of our knowledge, this deep blue laser has the highest cw output power among all available solid-state lasers. The setup of the deep blue laser is shown in Fig. 1. The pump source is a fiber-coupled laser diode that operates at 807.4 nm with a maximum output power of 40 W. Its emission central wavelength is 807.4 nm at room temperature and can be tuned by changing the temperature of the heat sink to match the best absorption of the laser crystal. The diameter of the fiber core is 400 μm with a numerical aperture of 0.22. The pump light is focused into the laser crystal by two plano–convex lenses. The coupling efficiency is 95% and the diameter of the pump waist imaged in the crystal is 220 μm. Because the pump intensity is high enough in the pump spot regions, the first lens must be well

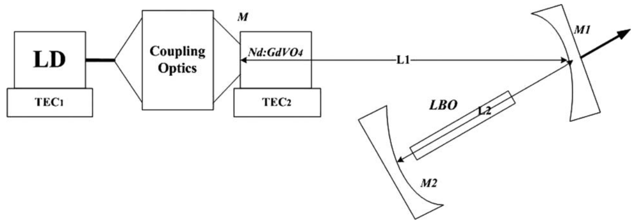

Fig. 1. Setup of the intracavity frequency-doubled $Nd:GdVO_4$ ground-state laser.

adjusted to collimate the pump beam, since it has a significant effect on the focal spot. However, the distance between the two lenses can be easily adjusted.

The $Nd:GdVO_4$ laser was introduced by Zagumennyi *et al.* [9] and has the same space group as the YVO_4 laser. The advantages of YVO_4 with regard to $Nd:YVO_4$ are a higher absorption cross section near 808 nm and twice the amount of thermal conductivity in the ⟨110⟩ direction, which reduces the reabsorption losses in ground-state lasers that are due to the thermal population of the lower laser level. $Nd:GdVO_4$ has a much higher thermal conductivity than $Nd:YVO_4$, even comparable with that of Nd:YAG, which enables its use as laser gain material to be high-power pumped. Another reason to use $Nd:GdVO_4$ as a solid-state laser is degeneration of the upper laser level [10] so that the entire inversion contributes to the gain. The weak thermal birefringence and weak thermal lens effect of low doped concentration and a large bulk laser crystal are suitable for $Nd:GdVO_4$ to be used as the laser crystal in our experiment. We used an a-cut, 0.1% doped, 3 mm x 3 mm x 3mm $Nd:GdVO_4$ crystal.

The left-hand side of the laser crystal was coated with antireflection films at a pump wavelength of 1063 nm ($R < 2\%$) and with high-reflection films at 912 nm ($R > 99.9\%$), acting as one mirror of the cavity. A long laser crystal with low-doped concentration was used to reduce thermal lensing and the reabsorption of quasi-three-level emission while guaranteeing that enough pump energy will be absorbed. The temperature of the laser crystal was kept at a constant of 15 °C by a thermoelectric cooler (TEC), which helps to maintain a small thermal population of the terminal laser level and provides stable output power. The lower temperature is essential for efficient operation at 912 nm of the $Nd:GdVO_4$. The right-hand side of the laser crystal was antireflection coated at 912, 1063, and 1341 nm to reduce loss of the resonating 914 nm oscillation and suppress the strong lines of 1063 and 1341 nm. When the coating requirements on the both sides of the $Nd:GdVO_4$ crystal are satisfied, the 912 nm spectral line can oscillate independently.

The radius of the concave face is 50 and 200 mm for M_1 and M_2, respectively. The concave face of M_1 has high reflectivity at 912 nm and high transmittivity at 1063, 1341, and 456 nm. The coating films for the plane surface are the same as for the right-hand side of the laser crystal except with high transmission at 456 nm. End mirror M_2 was high-reflection coated at 912 and 456 nm. L_1 and L_2 are the lengths of the arms in the cavity, each approximately 64 and 33 mm, respectively. The beam incident angle on the folded mirror was set to be as small as possible to reduce astigmatism without additional optical astigmatism-compensating elements. The laser diode array, the whole cavity, and the crystal were cooled with the TEC for active temperature control with a stability of $\pm 0.1 \times °C$. Lithium borate (LBO) is a 2 mm x 2 mm x 15 mm nonlinear crystal ($\theta = 90°$, $\varphi = 21.9°$). We selected LBO as the doubling material for our experiment because of its small walk-off angle and large spectral and angular acceptance bandwidths. Both facets of the LBO crystal were antireflection coated at 456 and 912 nm to reduce reflection loss in the cavity. The crystal was mounted in a copper block that was also fixed on a TEC to maintain active temperature control.

Figure 2 shows the output results of 456 nm as a function of incident pump power obtained with a 40 W fiber-coupled laser diode array. It is obvious that a high lasing threshold exists in the 456 nm blue laser because of the quasi-three-level structure of the 912 nm fundamental line. The diode-pumped $Nd:GdVO_4$ laser we used operates at the ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition at 912 nm in π polarization. The lower laser level is the highest sublevel of the ${}^4I_{9/2}$ multiple energy level. The lower laser level and the ground state are thermally coupled so that the reabsorption loss can significantly decrease the laser output power of the 912 nm laser and increase the laser threshold. According to the threshold equation of the quasi-three-level system, a decrease in the spot size of the pump beam could decrease the threshold. The smaller the spot of the pump beam, the more serious the diffraction loss and the mismatch of the mode-matching condition could make the slope efficiency descend. The absorption efficiency of the pump energy increases when the length of the laser crystal increases. However, the reabsorption phenomenon

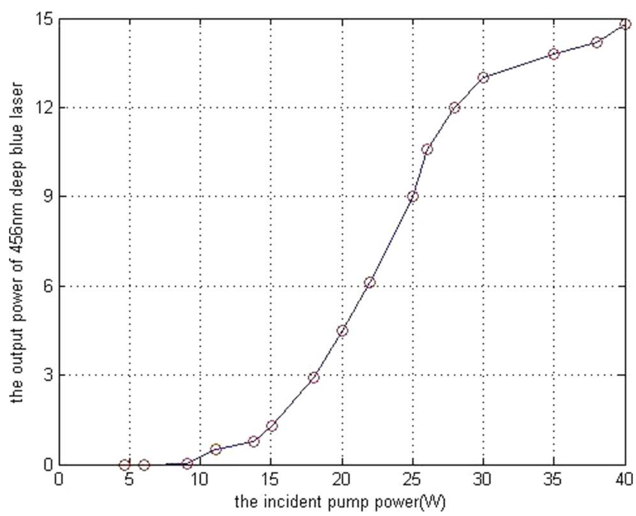

Fig. 2. (Color online) Output power at 456 nm as a function of incident pump power at 808 nm.

leads to the loss of a fundamental wave increase as well. So an optimal length of laser crystal exists in the laser operation of a quasi-three-level system. The parameter used in this experiment is under optimization. The length of the $Nd:GdVO_4$ crystal is approximately 5 mm, which balances the reabsorption loss and the laser slope efficiency. The threshold pump power shown in Fig. 2 is as high as 10 W. At a lower pump power, below 10 W, lower circulating intensity exists in the resonator and the corresponding high reabsorption loss leads to high threshold. With the increase in incident pump power, the turning point is when the 456 nm output power rises rapidly from tens of milliwatts to hundreds of milliwatts. The reason for this phenomenon is due to the saturation of reabsorption loss of the quasi-three-level system for the 912 nm fundamental wave. As the pump power increases, the circulating intensity becomes so high that it bleaches the reabsorption loss and the output power increases suddenly at this point. Afterward, the laser operates as a four-level system. When the incident pump power is 40 W, the output power is as high as 14.8 W as measured by filtering infrared 808 and 912 nm light; the optical-to-optical conversion efficiency is 37%. Obviously, when the pump power is greater than 30 W, the slope efficiency decreases. The reason for this phenomenon is that the laser crystal is equal to a thermal lens in the operation of a laser and its focal length decreases when the pump power is high and the stability of the three-mirror-fold cavity decreases with the increase in incident pump power. Further optimization of the resonator and better cooling conditions could solve this problem, which would result in higher efficiency.

The beam quality testing result is shown in Fig. 3, indicating that the laser output at 456 nm operates near the TEM_{00} mode. The far-field intensity of the beam is also displayed in Fig. 3 , which is near the Gaussian distribution. The stability of the output is better than 2.57% during 2 h of measurements with a LabMaster Ultima powermeter whose analog bandwidth is from 10 Hz to 50 kHz. The result shows that the laser output has low-power fluctuation. The source of noise in a frequency-doubled laser is due to the longitudinal mode cross saturation in the laser crystal and sum-frequency mixing in the double-frequency crystal. The polarization character of the $Nd:GdVO_4$ crystal and the function of LBO as a polarizer influence the noise of the 456 nm blue laser. The $Nd:GdVO_4$ crystal has a high pump beam absorption coefficient with π polarization and emits fundamental waves in the π direction with high efficiency. Based on the theoretical model described in Ref. [11], LBO serves as a polarizer except for a frequency-doubled crystal, which limits the oscillation of the fundamental wave that is vertical to the π direction. Since coupling the longitudinal modes that are vertical to each other is the source of the noise, the high polarization ratio of the 912 nm fundamental wave relieves coupling of orthogonal modes and eliminates the influence of sum-frequency generation on frequency doubling. A comparison of the 457 nm blue laser generated by the $Nd:GdVO_4$ crystal indicates that the larger thermal conductivity of the $Nd:GdVO_4$ crystal is attributed to a slight effect that the laser crystal temperature fluctuation has on the population of the lower level in a quasi-three-level laser system, which enhances laser efficiency as well as suppresses noise. In the experiment, the length of the cavity is approximately 105 mm and the number of longitudinal mode oscillations in the resonator is approximatgely 544. The $Nd:GdVO_4$ crystal has a broad gain linewidth that ensures that there is no longitudinal mode with enough peak gain to lead to the nonlinear loss of other modes. All the physical phenomena demonstrated above prove that the noise of the 456 nm blue laser can be significantly suppressed without the use of an additional element.

In summary, a compact and efficient cw end-pumped $Nd:GdVO_4/LBO$ deep blue laser at 456 nm has been demonstrated. A folded three-mirror cavity with an approximate length of 105 mm was optimized to obtain a highly efficient deep blue laser. Although the incident power is

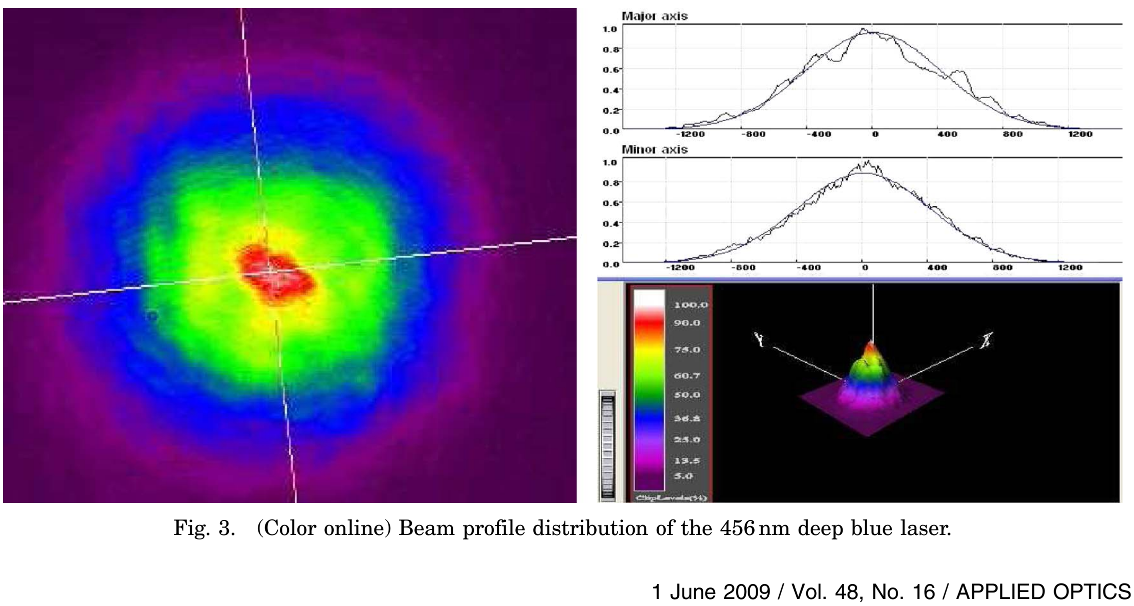

Fig. 3. (Color online) Beam profile distribution of the 456 nm deep blue laser.

40 W, we achieved a 14.8 W cw 456 nm deep blue laser. The optical-to-optical conversion efficiency was greater than 37% and the output power stability was better than 2.57% after 2 h of experimenting at an analog width of from 10 Hz to 50 kHz.

This research is supported by Changchun New Industries Optoelectronics Technology Company, Ltd.; www.cnilaser.com.

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