6.2-W deep blue light generation by intracavity frequency-doubled Nd:GdVO$_4$ using BiBO

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Efficient continuous-wave (CW) intracavity frequency doubling of a diode-end-pumped Nd:GdVO$_4$ laser operating on $^4F_{3/2}-{}^4I_{9/2}$ transitions at 912 nm has been demonstrated. A symmetrical cavity with two laser rods is designed, which divides the pump power between the two laser rods, allowing for greater power scalability. An 18-mm-long BiBO crystal, cut for critical type I phase matching, is used for the intracavity frequency-doubled laser. A maximum output power of 6.2 W in the blue spectral range at 456 nm has been achieved with the pump power of 36 W. The beam quality M^2 value is 2.5 in both horizontal and vertical directions. The ellipticity of the deep blue laser is 0.98, and the power stability is better than 3.2% at the maximum output power.

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Laser-diode (LD) pumped solid-state lasers in the visible spectral range have applications in the fields of measurement technique, printing and display technology. The LD pumped quasi-three-level Nd^{3+} laser, which operates on the $^4F_{3/2}-{}^4I_{9/2}$ transition, was first introduced by Fan *et al.*[1] who have realized a Nd:YAG laser at 946 nm. Also the generation of blue light at 473 nm was demonstrated with intracavity second harmonic generation (SHG). The highest continuous wave (CW) power achieved from such laser system so far has been 3.8 W at 473 nm[2]. In order to reach wavelengths in the deeper blue region (below 460 nm), other host crystals have to be investigated. Among such crystals, Nd:YVO$_4$ is an attractive well known material and an intracavity doubled Nd:YVO$_4$ ground-state laser exhibiting 12 mW of output power at 457 nm is available commercially[3]. LD pumped Nd:GdVO$_4$ lasers operating at 1.06 and 1.34 μm have already been developed. Also SHGs to the green and red spectral regions have been demonstrated[4,5]. Recently, a blue laser with Nd:GdVO$_4$ as host material has been demonstrated by Jia *et al.*[6], the output power was 5.3 W[6]. In this paper we report a Nd:GdVO$_4$ laser with 6.2-W output power at 456 nm, it is the highest to our knowledge.

The diode-pumped Nd:GdVO$_4$ laser presented in this paper operates on the $^4F_{3/2}-{}^4I_{9/2}$ transition at 912 nm in π-polarization. The lower laser level is the highest sublevel of the $^4I_{9/2}$ multiplet. A schematic of the intracavity deep-blue laser is shown in Fig. 1, which is a symmetrical cavity with two Nd:GdVO$_4$ crystals. This design could shift the stability range to higher pump power, with the advantage of dividing the pump power between the two Nd:GdVO$_4$ rods. The laser crystal is a $3\times3\times5$ (mm), 1% Nd^{3+}-doped GdVO$_4$. The sides of the laser crystal were coated for high-transmission (HT) at 912 nm and the pump wavelength. HT at 1062 and 1341 nm was also specified to prevent parasitic oscillations on these Nd:GdVO$_4$ transitions. In order to decrease the influence of the thermal effects, the laser crystal was water-cooled. The high-brightness fiber-coupled LD served as the pump. It delivered a maximum output power of 20 W at 808 nm from the end of a fiber with 400-μm core diameter and a numberical aperture (NA) of 0.22. The pump light is focused by four achromatic lenses into the laser crystal, where the diameter at the focus is 15 mm. The sides of the laser crystals were looked as the input mirrors, M1 and M4, with antireflection (AR) coating at 808 nm and high-reflection (HR) coating at 912 nm. In addition, the mirrors had sufficient transmission at 1062 and 1341 nm. Two curved folding mirrors (R = 100 mm), M2 and M3, had HR coating at 912 nm and AR coating at 456 nm. An 18-mm-long BiBO crystal, cut for critical type I phase matching ($\theta = 45.4°$, $\phi = 0°$), was used as the frequency-doubling crystal, which had an AR coating at 1062 and 456 nm.

Figure 2 shows the radii of the laser mode in the middle of the laser crystal and the frequency-doubling

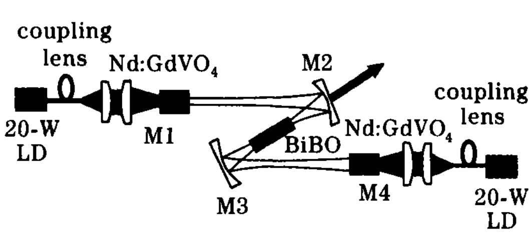

Fig. 1. Schematic of the experimental setup.

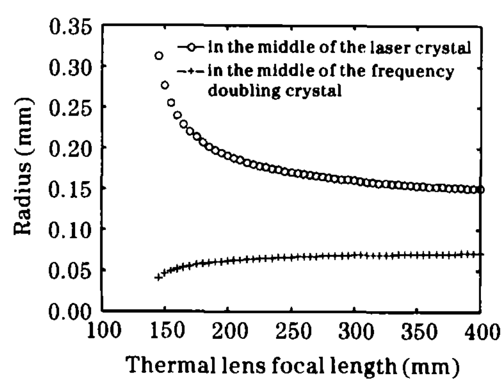

Fig. 2. Radii of the laser mode in the middle of the laser crystal and the frequency doubling crystal versus the thermal lens focal length.

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crystal. The radius in the laser crystal is about 0.16 mm and matched the pump mode in a region of the thermal lens focal length from 200 to 300 mm. Therefore, such a laser can stably operate with high pump power. The BiBO crystal is placed in the focus of the laser mode between the curved mirrors M2 and M3 to yield a small focus (about 0.7 mm in the center of the BiBO crystal) and good doubling efficiency. Moreover, it is not necessary to adjust the location of the frequency doubling crystal while increasing the pump power. The data were calculated by the *ABCD* matrix formalism with the approximation of a thin lens in the middle of the laser crystal.

After 808-, 1062-, 1341-, and 912-nm lights were filtered, a power meter with precision of 10 nW was used to measure 456-nm laser output. The curve of deep blue laser power as a function of pumping light is shown in Fig. 3. The pump power given in this paper is summed

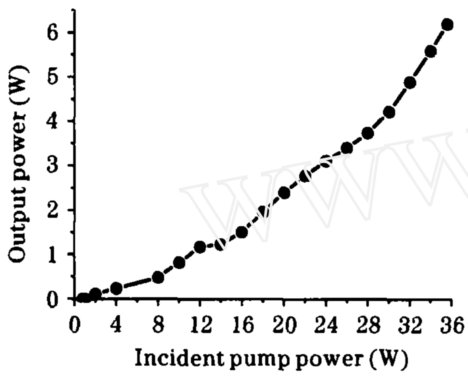

Fig. 3. 456-nm laser output power versus incident pump power.

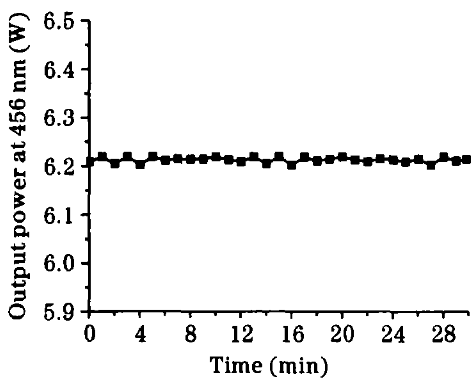

Fig. 4. Stability of the deep blue output power around the 6.2-W operation point.

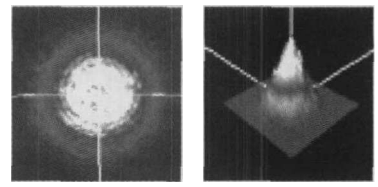

Fig. 5. TEM_{00} energy distribution of far-field spots.

values of the two powers. It is shown that threshold of pump power was about 2.6 W. When 36-W pumping light was injected, 6.2-W, 456-nm output was obtained, and no saturation appeared. Figure 4 is the output power of the 456-nm deep blue laser as a function of time around the output power of 6.2 W. It is shown that the power stability is better than 3.2%. The TEM_{00} energy distribution diagrams of 456-nm laser far spot recorded by a beam profiler (made by Photon Inc.) is shown in Fig. 5, the ellipticity of spot is 0.98.

In summary, a diode-pumped CW deep blue laser at 456 nm has been demonstrated with the maximum output power of 6.2 W by using a symmetrical cavity with two $Nd:GdVO_4$ crystals. To the best of our knowledge, this experimental result is the highest power reported for an all solid-state CW deep blue laser at 456 nm. The beam quality M^2 value was equal to 2.5 in both transverse directions at the maximum output power. The ellipticity of the deep blue laser is 0.98, and the power stability is better than 3.2% at the maximum output power.

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