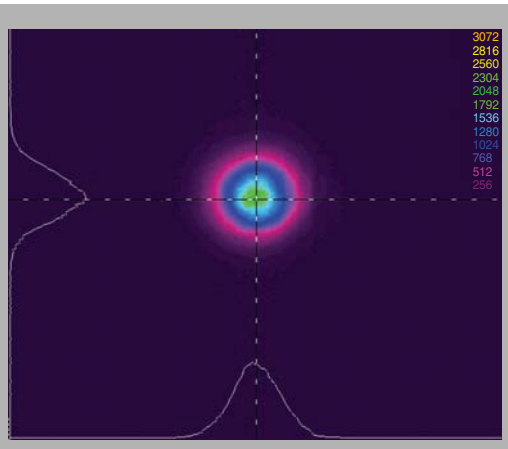
Abstract: We report a diode-pumped Nd:YAG laser emitting at 899 nm based on the $^4F_{3/2} - {}^4I_{9/2}$ transition. A power of 1.04 W at 899 nm has been achieved in continuous-wave operation with a fiber-coupled laser diode emitting 19.2 W at 809 nm. Furthermore, intracavity second-harmonic generation in continuous-wave mode has also been demonstrated with a power of 284 mW at 449.5 nm by using a BiB_3O_6 (BiBO) nonlinear crystal. The fluctuation of the blue output power was better than 2.8%. The beam quality M^2 value is 1.3.



Far-field beam spatial profile of 449.5 nm blue laser

Diode-pumped Nd:YAG/BiB_3O_6 deep-blue laser at 449.5 nm

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1. Introduction

In recent years, much attention has been paid to efficient, compact all-solid-state visible-wavelength lasers for some applications, such as fluorescence spectroscopy, display, flow cytometry, and underwater communications. These past few years there has been research to reach wavelengths deeper in the blue. For diode-pumped solid-state lasers there are two ways to reach this range. One way is to design lasers with crystals doped with ions directly emitting in the blue, such as Dy^{3+} [1]. The other way is to develop lasers emitting at the lowest wavelength possible in the near infrared [2] and to perform nonlinear conversion. Classical wavelengths of frequency doubled solid-state blue lasers are 473 nm (Nd:YAG laser) [3,4], 457 nm (Nd:YVO_4 laser) [5–7], 456 nm (Nd:$GdVO_4$ laser) [8–10], and 458 nm (Nd:$LuVO_4$ laser) [11,12]. These lasers are efficient and powerful, and it could be interesting to extend these sources to other wavelengths, in particular to deeper blue. In neodymium-doped crystals the transition offering the lowest wavelengths is the $^4F_{3/2} - {}^4I_{9/2}$. This transition is usually used to design lasers around 910 nm in vanadate crystals [13–18] or at 946 nm in YAG crystal [19–22]. In these cases, the laser system is a quasi-three-level one, the lower laser level of the transition being the highest sublevel of the fundamental manifold.

The lowest wavelengths ever reported with diode-pumped solid-state lasers based on Nd ions are 903 nm with Nd:YLF [23], 900 nm with Nd:ASL [24,25], and re-

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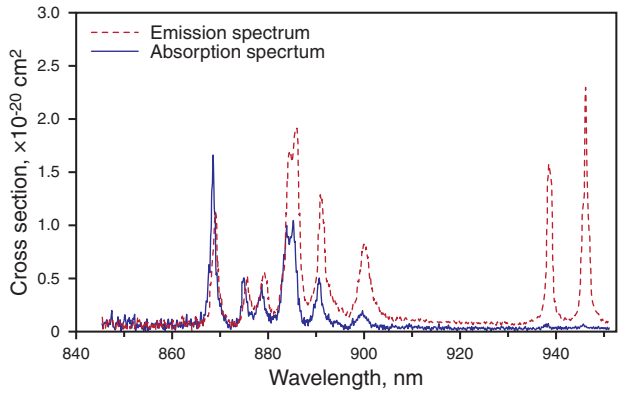

Figure 1 (online color at www.lphys.org) Room-temperature emission and absorption cross-sections of Nd:YAG crystal

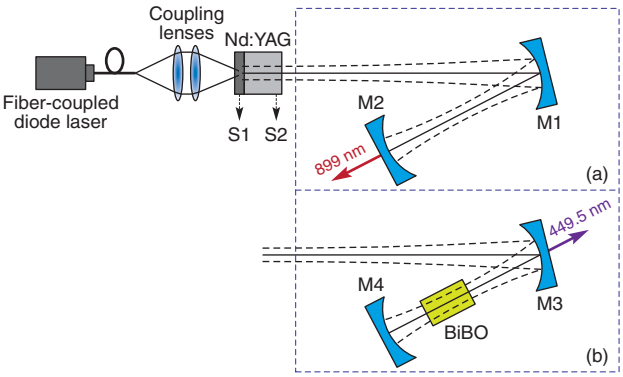

Figure 2 (online color at www.lphys.org) Experimental setup. The distances of S1 – M1 (or M3), and of M1 – M2 (or M4) were 67 and 28 mm, respectively

cently 884 – 899 nm in Nd:YAG and 879 nm in Nd:$GdVO_4$ [26,27]. In particular, the $^4F_{3/2} - {}^4I_{9/2}$ transition can offer other possibilities at lower wavelengths. Emission and absorption spectra of Nd:YAG crystal are shown in Fig. 1 ([25]). Frequency doubling of the ground-state laser transition of neodymium-doped laser hosts is a promising possibility to obtain high output power in the blue spectral region.

In this letter we report a diode-pumped Nd:YAG laser emitting at 899 nm based on the $^4F_{3/2} - {}^4I_{9/2}$ transition. In addition, intracavity second-harmonic generation was obtained in continuous-wave operation by using a nonlinear BiBO crystal to reach deep-blue emission at 449.5 nm.

2. Experimental setup

The experiment setup of the fundamental 899 nm laser is shown in Fig. 2a. The pump source was a fiber-coupled

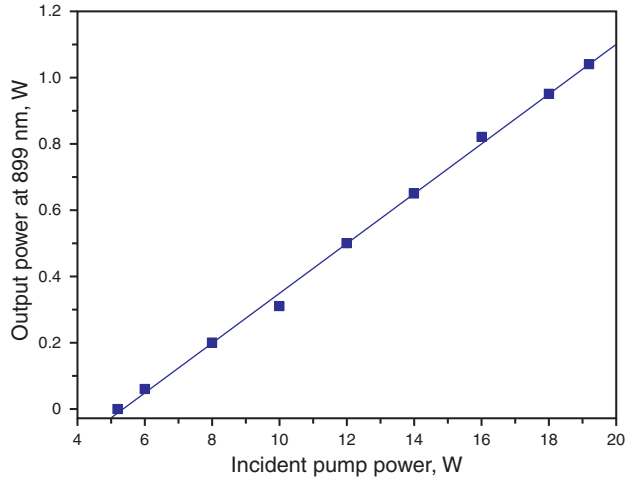

Figure 3 (online color at www.lphys.org) Output power at 899 nm *versus* incident pump power

diode at 809 nm with a core diameter of 400 μm and a numerical aperture of 0.22, and provided a maximal power of 20 W. An optical system made of two achromatic lenses was employed in order to image the fiber end into the Nd:YAG crystal. The waist of pump beams was measured to have a radius of nearly 190 μm. The Nd:YAG crystal (0.5 at.% doping level, 3 mm long) has the pumping side (S1) was coated for antireflection (AR) at 809 nm, and high reflectivity (HR) at 899 nm. The opposite side (S2) was coated for AR at 899 nm in order to increase the pumping beam absorption efficiency. The crystal was wrapped in indium foil and placed in a copper holder, whose temperature was kept at 15°C through a thermoelectric cooler. A plano-concave mirror (M1) with a curvature radius of 200 mm was coated for antireflection (AR) at 946 nm and 1064 nm, and HR at 899 nm. The output mirror (M2) with a curvature radius of 50 mm was employed, with a transmission of 3% at 899 nm.

The experiment setup of the 449.5 nm blue laser is shown in Fig. 2b. All the elements were the same as the corresponding ones in the setup of fundamental 899 nm laser mentioned above. The plano-concave mirror M4 ($\rho = 200$ mm) was coated for HR at 899 nm and 449.5 nm and AR at 946 nm and 1064 nm. The output mirror M3 ($\rho = 50$ mm) was coated for HR at 899 nm and AR coated at 449.5 nm. An BiBO crystal cut for type-I critical phase matching in the principal plane XZ ($\theta = 136°$, $\phi = 90°$) with $d_{eff} = 2.48$ pm/V) was chosen as the nonlinear crystal. The size of the BiBO crystal is $2 \times 2 \times 10$ mm^3 and both end faces were coated for AR at 899 nm and 449.5 nm wavelengths. It was wrapped with a thin indium foil and mounted in a copper holder, which was cooled by a thermoelectric cooler for an active temperature control with the stability of 27±0.1°C.

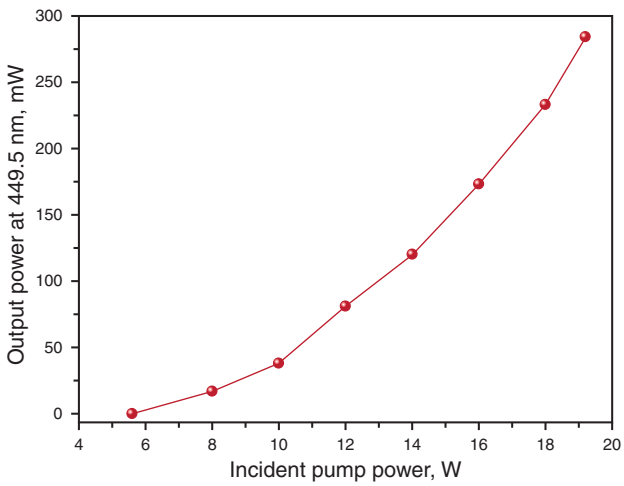

Figure 4 (online color at www.lphys.org) Output power at 449.5 nm *versus* incident pump power

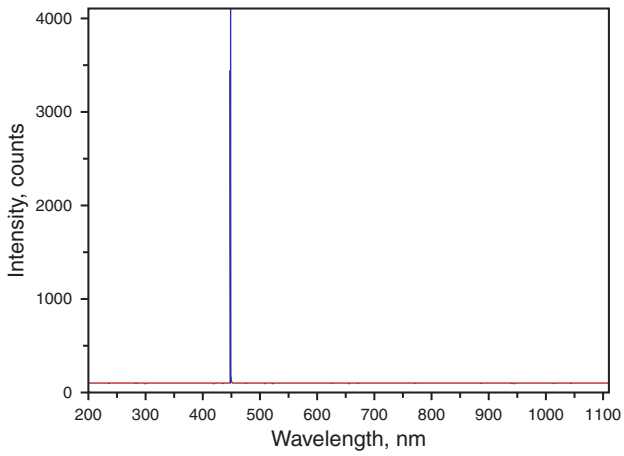

Figure 5 (online color at www.lphys.org) The laser spectrum line of 449.5 nm blue laser

3. Results and discussions

The output power at 899 nm *versus* the pump power measured is shown in Fig. 3. Laser emission at wavelengths other than 899 nm can be achieved by inserting a Fabry-Perot etalon into the cavity. Thus, lasing oscillation has been demonstrated without other line competition. We obtained a maximum output power around 1.04 W for 19.2 W incident pump power, and a threshold of 5.2 W. Fig. 4 shows the continuous-wave 449.5 nm power as a function of incident pump power at 809 nm. The maximum output power of 284 mW was obtained with incident pump power of 19.2 W. Fig. 5 shows the spectra of 449.5 nm deep-blue laser which was detected using the high resolution spectrometer.

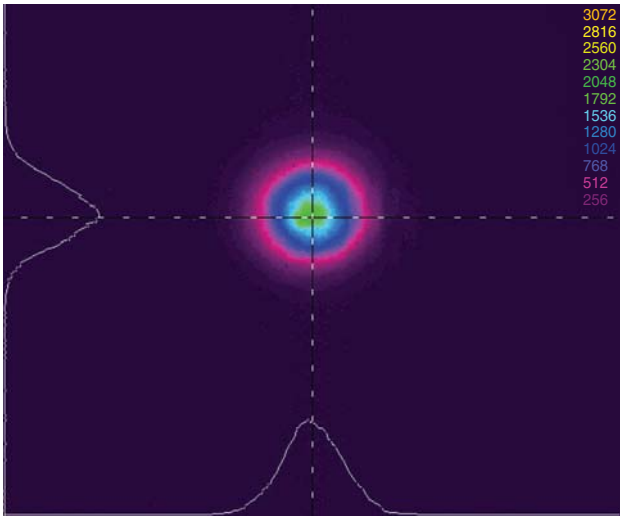

Figure 6 (online color at www.lphys.org) Far-field beam spatial profile of 449.5 nm blue laser

The far-field beam spatial profile of the 449.5 nm laser was measured by a laser beam diagnostics. Fig. 6 is the beam profile testing result, which shows that the laser output at 449.5 nm is operating at near TEM_{00} mode. The beam quality factor M^2 is 1.3 measured by the knife-edge technique. Stability of better than 2.8% for 4 hour is measured by Field Master-GS power meter.

4. Conclusion

In conclusion, we have demonstrated diode-pumped Nd:YAG laser emitting at 899 nm with a maximum continuous-wave output power of 1.04 W for 19.2 W of incident pump power at 809 nm. Furthermore, intracavity second harmonic generation has also been demonstrated with a power of 284 mW at 449.5 nm by using a BiBO nonlinear crystal. Thus, this experiment opens a new way to reach deepest wavelengths in the blue range. Further, the use of more efficient nonlinear crystals, such as ppKTP or $KNbO_3$, should increase the blue power.

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