Highly efficient Nd:YAG/LBO laser at 473 nm under direct 885-nm diode laser pumping

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In diode pumped Nd:YAG lasers, the quantum defect is the most important parameter determining the thermal load of the laser crystal, which can be dramatically reduced by pumping directly into the upper laser level. A compact folded three-mirror cavity with a length of 105 mm is optimized to obtain a highly efficient 473-nm laser. When the absorbed pump power (with 15.8-W incident pump power) at 885 nm into Nd:YAG is 10 W, a continuous-wave 473-nm blue laser as high as 2.34 W is achieved by LBO intra-cavity frequency doubled. The optical-to-optical conversion efficiency is 14.8%. To the best of our knowledge, this is the highest efficiency at 473 nm by an intra-cavity doubled frequency Nd:YAG laser.

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Several applications such as laser display, spectroscopy, and underwater communication require multiwatt power level in the blue region of the visible spectrum. Fan *et al.* introduced a diode-end-pumped Nd:YAG laser operating on $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transitions of 946 nm at room temperature in 1987[1], and then the 473-nm blue light produced by intracavity second harmonic generation was extensively studied[2−10]. Recently, Chen *et al.* reported that the maximum output of 2.1 W at 473-nm continuous wave (CW) was generated with LBO intracavity frequency doubling under a pump diode power of 23 W with an optical-to-optical efficiency of 9.1%[11]. To our best knowledge, the highest CW output power achieved from such a laser so far was 3.8 W at 473 nm by intracavity frequency doubled Nd:YAG/LBO laser[12], and the corresponding optical-to-optical conversion efficiency was 9.7%.

The quantum defect between the pump and the laser emission wavelengths is a major limitation in the scaling of the solid state lasers to high power, which influences the emission characteristics, such as the laser threshold and the slope efficiency, and has a major contribution to the heat generation in the laser material. Thus, the reduction of the quantum defect is an important issue in the diminution of heat, and for Nd^{3+} laser materials this can be accomplished by pumping directly into the emitting level of $^4F_{3/2}$. Direct pumping into the emitting level was proposed by Lupei *et al.*[13,14]. Using diode laser pumping $Nd:YVO_4$, $Nd:GdVO_4$, and $NdAl_3s(BO_3)_4$ lasers were recently demonstrated[15−20]. There are some highly efficient end-pumped Nd:YAG lasers with direct pumping into the upper laser level by reducing the quantum defect, which get much more advantages than the indirect pumping by using 808-nm pumping laser[21−23].

In this letter, a compact folded three-mirror resonator is designed. A compact efficient CW 473-nm blue laser is achieved under direct 885-nm diode laser pumped Nd:YAG and intra-cavity doubled frequency by LBO. The overall optical-to-optical efficiency of 14.8% is obtained.

The energy level diagram of Nd:YAG is shown in Fig. 1. Process A indicates the traditional 808-nm pumping. The laser active ions are pumped from the Z_1 sub-level of the $^4I_{9/2}$ ground-state level to the $^4F_{5/2}$ level, and then relax to the $^4F_{3/2}$ upper lasing level with heat generation. Process B indicates the 885-nm direct pumping which is to pump laser active ions from the Z_2 sub-level of the $^4I_{9/2}$ ground-state level directly to the R_1 sub-level of the $^4F_{3/2}$ level without relaxation process, while the process C indicates the laser emission of 946 nm. A further increase of slope efficiency could be expected due to the fact that the quantum efficiency for the pump to upper laser level transition is not unity but can be neglected by direct upper laser level pumping. The overall quantum defect ratio λ_p/λ_e (λ_p is the pump wavelength, λ_e is the emission wavelength) by using the pump at 885 nm can be enhanced from 0.85 to 0.94 for 946-nm emission with respect to that obtained under 808-nm pump, leading to a reduction of the fractional thermal load and an increase of the slope and optical

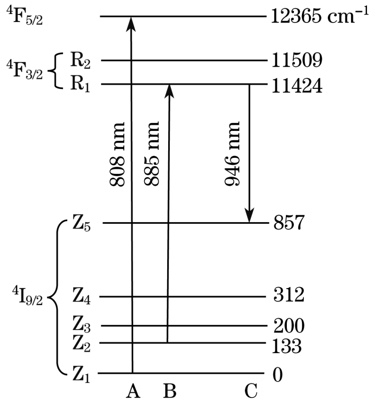

Fig. 1. Energy level diagram of Nd:YAG.

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efficiencies. Moreover, the effect on the fractional thermal loading is much larger, implying an expected reduction of 30 − 50% of the function on the laser threshold[24]. The rise of the temperature caused by the non-radiative processes in a pumped laser material is proportional to the absorbed power transformed into heat. Since the energy of the emitting level R1 for 946-nm emission is larger than the quantum energy of the 885-nm radiation, this regime of pumping is endothermic, with the difference being supplied by the crystalline lattice vibrations. This endothermic contribution represents more than 12% of the total reduction of heat generation when shifting from 808- to 885-nm pumping[24].

The layout of the compact intra-cavity doubled Nd:YAG/LBO blue laser at 473 nm is shown in Fig. 2. The optical pumping at 885 nm was made with a 400-μm diameter, 0.22 number aperture fiber-coupled diode laser. Similarly, the experiment was also developed, with the optical pumping source at 808 nm. A 1:1 achromatic optical system was employed to image the fiber end into the laser crystal. The active medium was a 1.0-at.% Nd^{3+}, 3-mm-long Nd:YAG crystal. The laser crystal was wrapped with indium foil and mounted in a water-cooled copper block. The water temperature was maintained at 25 °C. Both sides of the laser crystal were coated for high transmission (T) at 1064, 1319, and 946 nm.

The flat mirror M1 was coated for high reflection (R) at 946 nm. The 50-mm radius of curvature concave mirror M2 is an output coupler for 473 nm, with high transmission at 473 nm ($T \approx 98\%$) and high reflection at 946 nm ($R \approx 99.9\%$). The 200-mm radius of curvature concave mirror M3 was coated for high reflection at 946 and 473 nm (R(946 nm) $\approx 99.9\%$, R(473 nm) $\approx 99.9\%$).

The coatings of the three mirrors and the Nd:YAG have the transmissions greater than 70% at 1064 and 1319 nm. The high transmission at 1064 and 1319 nm for the components is necessary since the gain of the oscillation line at 1064 and 1319 nm is much higher than that at 946 nm. The highly wavelength-selective dielectric coatings suppress the laser oscillation at the strongest transition of 1064 and 1319 nm, and provide optimum conditions at 946 nm. Each face of the elements in the cavity was coated for high transmission at 946 and 473 nm to minimize the insertion losses. Type I critical phase-matching 10-mm-long LBO non-linear crystal ($\theta = 90°$, $\varphi = 19.3°$ at 300 K) is used to double frequency 946 nm in the resonator. Two arms constitute the folded three-mirror resonator. One is the collimating arm ($l_1 =$ 71 mm) which has a larger beam waist radius ($\omega_{01} =$ 200 μm) in the middle of Nd:YAG, and the other is the focusing arm ($l_2 =$34 mm) which has a smaller beam waist radius ($\omega_{02} = 60$ μm) in LBO.

The output power at 473 nm for 1.0-at.% Nd:YAG under 808 and 885 nm pumping was measured with a laser powermeter, respectively. The results are plotted in Fig. 3. In the case of 808-nm pumping, the maximum output power of 1.21 W was obtained for 10-W absorbed pump power (or 10.2-W incident pump power), leading to an optical-to-optical conversion efficiency of 11.8%. In the case of 885-nm pumping, the maximum output power of 2.34 W was obtained for 10-W absorbed pump power (or 15.8-W incident pump power), leading to an optical-to-optical conversion efficiency of 14.8%. Contrast with the 808-nm pumping, the higher optical-to-optical conversion efficiency is obtained by direct pumping at 885 nm. This is mainly resulted from the larger Stokes factor of ~8% under 885-nm pumping than that under 808-nm pumping. Besides, the optimization of plano-concave cavity is also an important contributing factor. Moreover, the smaller quantum defect ratio induced by the heat generation in 885-nm pumping than that in 808-nm pumping can also improve the laser parameters.

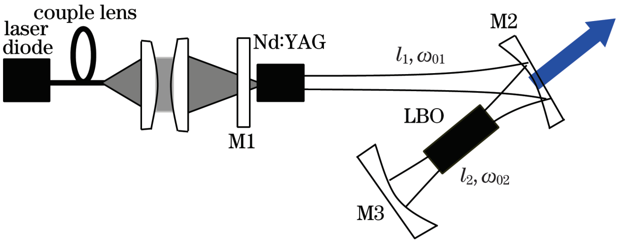

Fig. 2. Schematic setup of the blue laser at 473 nm.

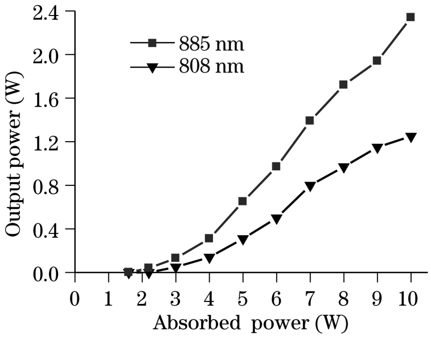

Fig. 3. Emission characteristics of 473-nm laser under 885- and 808-nm pumping.

In conclusion, a compact efficient CW end-pumped Nd:YAG/LBO blue laser at 473 nm is demonstrated. A folded three-mirror cavity with length of 105 mm is optimized to obtain the highly efficient blue laser. When the direct pumping power at 885 nm into Nd:YAG is 15.8 W, a CW 473-nm blue laser as high as 2.34 W is achieved. The optical-to-optical conversion efficiency is 14.8%. To the best of our knowledge, this is the highest efficiency at 473 nm by an intra-cavity doubled frequency Nd:YAG laser. According to the experimental results, the conversion efficiency with direct pumping at 885 nm is evidently higher than the traditional pumping at 808 nm. The results of this work demonstrate that the diode laser pumping into the emitting level of Nd^{3+} laser crystal is a solution for the construction of efficient lasers and the scaling to high power.

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References

1. T. Y. Fan and R. L. Byer, Opt. Lett. **12,** 809 (1987).
2. W. P. Risk, R. Pon, and W. Lenth, Appl. Phys. Lett. **54,** 1625 (1989).

3. Q. Zheng and L. Zhao, Opt. Laser Technol. **36,** 449 (2004).
4. P. Li, D. Li, Z. Zhang, and S. Zhang, Opt. Commun. **215,** 159 (2003).
5. C. Czeranowsky, E. Heumann, and G. Huber, Opt. Lett. **28,** 432 (2003).
6. X. Lin, R. Li, D. Cui, A. Yao, Y. Feng, Y. Bi, and Z. Xu, Chin. Phys. Lett. **19,** 1106 (2002).
7. Q. Xue, Q. Zhen, J. Wang, and Z. Ye, Chinese J. Lasers (in Chinese) **31,** 919 (2004).
8. J. Wang, Q. Zheng, Q. Xue, and H. Tan, Chinese J. Lasers (in Chinese) **31,** 523 (2004).
9. L. Gao and H. Tan, Chinese J. Lasers (in Chinese) **31,** 1033 (2004).
10. L. Gao and H. Tan, Opt. Laser Technol. **35,** 575 (2003).
11. Y. Chen, W. Hou, H. Peng, A. Geng, Y. Zhou, D. Cui, and Z. Xu, Chin. Phys. Lett. **23,** 1479 (2006).
12. Y. Chen, H. Peng, W. Hou, Q. Peng, A. Geng, L. Guo, D. Cui, and Z. Xu, Appl. Phys. B **83,** 241 (2006).
13. V. Lupei, N. Pavel, and T. Taira, Appl. Phys. Lett. **81,** 2677 (2002).
14. V. Lupei, N. Pavel, and T. Taira, Appl. Phys. Lett. **83,** 3653 (2003).
15. Z. Huang, Y. Huang, Y. Chen, and Z. Luo, J. Opt. Soc. Am. B **22,** 2564 (2005).
16. Y. Sato, T. Taira, N. Pavel, and V. Lupei, Appl. Phys. Lett. **82,** 844 (2003).
17. E. Herault, F. Balembois, and P. Georges, Opt. Lett. **31,** 2731 (2006).
18. X. Ding, R. Wang, H. Zhang, X. Yu, W. Wen, P. Wang, and J. Yao, Opt. Commun. **282,** 981 (2009).
19. Z. D. Luo, Y. D. Huang, M. Montes, and D. Jaque, Appl. Phys. Lett. **85,** 715 (2004).
20. M. Montes, D. Jaque, L. Zundu, and Hunag Yidong, Opt. Lett. **30,** 397 (2005).
21. V. Lupei, N. Pavel, and T. Taira, Opt. Lett. **26,** 1678 (2001).
22. N. Pavel, V. Lupei, J. Saikawa, T. Taira, and H. Kan, Appl. Phys. B **82,** 599 (2006).
23. M. Frede, D. Freiburg, R. Wilhelm, and D. Kracht, Proc. SPIE **6451,** 64510G (2007).
24. V. Lupei, G. Aka, and D. Vivien, Opt. Commun. **204,** 399 (2002).