High power doubly resonant all-intracavity deep blue laser at 447 nm based on sum-frequency-mixing technology

Yongji Yu (于永吉)*, Guangyong Jin (金光勇), Chao Wang (王 超), Xinyu Chen (陈薪羽), Jiaxi Guo (郭家喜), and Yibo Wang (王奕博)

Institute of Laser Technology, School of Science, Changchun University of Science and Technology,

*E-mail: yuyongjiyuyongji@163.com

Received February 20, 2009

A high power continuous-wave deep blue laser at 447 nm is obtained by using a doubly cavity and a type Π critical phase matching KTP crystal for intracavity sum-frequency-mixing. With the incident pump power of 240 W for the Nd:YAP crystal and 120 W for the other Nd:YAP crystal, the deep blue laser output of 5.7 W at 447 nm with near fundamental mode is obtained, and the beam quality M^2 value equals 2.53 in both horizontal and vertical directions at the maximum output power. The power stability is better than 2% at the maximum output power during half an hour. The experimental results show that the intracavity sum-frequency mixing by doubly resonant is an effective method for high power blue laser.

OCIS codes: 140.3530, 140.3480, 140.4780, 140.7300.

doi: 10.3788/COL20090711.1024.

Blue lasers have advantages of short wavelength, high photon energy, far transmission distance under the water, and eye-sensitive. So it is widely used in optical data storage, laser color display, underwater communication, biomedical, Raman spectrum, and quantum optics etc.^[1-3] In recent years, the method of laser diode (LD)</sup> end-pumped working substance doped Nd^{3+} to obtain ${}^{4}F_{3/2} \rightarrow {}^{4}I_{9/2}$ energy level translation, and using nonlinear crystal frequency doubling to obtain blue lasers has been widely used^[4-8]. However, because the ${}^{4}F_{3/2} \rightarrow {}^{4}I_{9/2}$ energy level translation of Nd^{3+} ion belongs to a quasithree-level system, and considering the small emission cross section and excessive start-up threshold results from re-absorption loss, the method constrains the further improvement of blue laser high-power output. A 1.3- μ m spectral line produced by the ${}^{4}F_{3/2} \rightarrow {}^{4}I_{13/2}$ energy level translation can also obtain blue laser through the adoption of third harmonic generation (THG). Although THG conversion efficiency is lower than second harmonic generation (SHG), the ${}^{4}F_{3/2} \rightarrow {}^{4}I_{13/2}$ translation has larger emission cross section and lower thermal effect. So it is a potential way to improve the output power of blue lasers. So far, the reported highest average output power of the blue lasers used this method to obtain an 7.6-W average power of quasi-continuous-wave (QCW) blue laser with the pump power of 480 $W^{[9]}$. In this letter, we firstly report a doubly cavity structure and intracavity sum-frequency to achieve high power 447-nm laser output through the optimum designing of the cavity. A fundamental frequency laser with 1341.4 nm and a frequency-doubled laser with 670.7 nm can oscillate and obtain respectively independent gain. Current of both side pump sources are adjusted to obtain oscillating beam of two sub-cavities closed. At the overlap region of two sub-cavity using a type Π critical phase matching KTP crystal for intracavity sum-frequency-mixing, it can obtain the deep blue laser at 447 nm of 5.7 W.

Among the neodymium-doped crystals, the Nd:YAP crystal has not only a higher thermal conductivity,

but also bigger stimulated emission cross section at ${}^{4}F_{3/2} \rightarrow {}^{4}I_{13/2}$ transition. And its natural birefringence characteristic can overcome depolarization loss caused by thermally induced birefringence with high average power. So it is one of the most suitable laser crystals for high-power operation at 1.3- μ m wave-band^[10]. The experimental device of the 447-nm blue laser with a doubly cavity structure is shown in Fig. 1. Each pump source includes 12 laser diode arrays (LDAS) with the maximum output power of 20 W and a Nd:YAP crystal rod. The size of the Nd:YAP crystal is $\Phi 3 \times 50$ (mm), b-axis cut off, and the Nd^{3+} doping concentration is 1%. In order to restrict self-excited oscillation of 1079-nm strong emission lines inside the crystal, both ends of the Nd:YAP crystal are coated with anti-reflection (AR) coatings at 1341.4 and 1079 nm. LDA symmetrically pumps the Nd:YAP rods from three-directions of the side. Simulation distribution of pump intensity is shown in Fig. 2. LDA and laser crystal use constant temperature circulation watercooled refrigeration. The temperature is controlled at 20 °C, and the central emission wavelength of LD is 808 nm. In the whole setup, there are three oscillatory cavity mirrors, M1, M2, and M3 of fundamental frequency laser at 1341.4 nm and the mirrors of frequency doubled laser at 670.7 nm are M4, M2, and M5. The surface of the convex mirror M1 (radius of curvature $R_{\rm c} = -200$ mm) was coated with high-reflection (HR) coatings at 1341.4 nm (R > 99.9%) and AR at 1079 nm (T > 70%). The beam splitter M2 $(R_c = \infty)$ was made from 1-mm thickness K9 glass by double-sided coating. The left side of M2 was coated with hightransmission (HT) coatings for 1341.4 nm (T > 99.9%)at 45° and the other side was coated with HT for 1341.4nm (T > 99.9%) at 45° and HR for 670.7 nm (R > 99.9%) at 45°. The concave of output mirror M3 ($R_c =$ 500 mm) was coated with HR at 1341.4 and 670.7 nm(R > 99.9%) and HT at 447 nm (T > 95%) and the other side HT at 447 nm (T > 95%). M4 ($R_c = \infty$) was coated with HR at 1341.1 nm (R > 99.9%) and AR at

Changchun 130022, China

1079 nm (T > 70%). The concave of M5 $(R_c = 500$ mm) was coated with HR at 1341.4 and 670.7 nm (R >99.9%). The double-frequency crystal of LBO was used with dimension of $4 \times 4 \times 20$ (mm) and the type-I critical phase matching $(e+e\rightarrow o)$ near M5. Calculated by the software $SNLO^{[11]}$, the crystal was cut along the xz-axis angle at $\theta = 86.1^{\circ}$ and $\phi = 0^{\circ}$. the effective nonlinear coefficient is 0.817 pm/V and the walk-off angle is 3.46 mrad. Both ends of the crystal were coated with double-color AR films for 1341.4 and 670.7 nm. The sum-frequency crystal of KTP was used with dimension of $4 \times 4 \times 10$ (mm) and the type- Π critical phase matching $(o+e\rightarrow o)$. Calculated by SNLO, the crystal was cut along the *xz*-axis angle at $\theta = 78.7^{\circ}$ and $\phi = 0^{\circ}$. Both ends of the KTP crystal were coated with three-color AR films for 1341.4, 670.7, and 447 nm. The KTP provided the THG 447-nm laser generation due to a larger effective nonlinear coefficient (4.04 pm/V) and a smaller change of the phase-matching direction in the temperature dependence^[11]. Each of the nonlinear crystals was wrapped with a thin indium foil and mounted in a copper holder whose temperature was maintained at 300 K by a thermal energy converter (TEC) cooler with an accuracy of ± 0.1 K. Based on the doubly cavity design, the sum-frequency crystal KTP was set overlapping region by two sub-cavities between M2 and M3.

Because of the high power LDA side-pumped gain medium, the thermal lens effect of gain medium is not a key factor for obtaining a high-efficiency and highpower output. Therefore, in a larger changing range of pump power, we attained thermal insensitive cavity by choosing the length of cavity reasonably. It is necessary to obtain stable high-power laser output. Through high precision bounded stable cavity method, we measured the thermal-lens focal length of the Nd:YAP rod^[12,13]. Figure 3 is thermal-lens focal length of Nd:YAP rod at



Fig. 1. Experimental setup of the 447-nm deep blue laser.



Fig. 2. Pumping light intensity distribution in Nd:YAP rod. (a) Three-dimentional view; (b) cross-sectional view.

different pump powers. In order to obtain higher sumfrequency efficiency, the injection power of fundamental frequency laser at $\lambda_1 = 1341.4$ nm and the frequency doubled laser at $\lambda_2 = 670.7$ nm were required to reach a certain ratio. The frequency of the laser beam were $\omega_1 = 2\pi c/\lambda_1$ and $\omega_2 = 2\pi c/\lambda_2$ (c is the velocity of light in vacuum). They have interaction in sum-frequency crystal, so nonlinear polarization intensity $P^{(2)}(\omega_3 = \omega_1 + \omega_2)$ is produced, where $\omega_3 = 2\pi c/\lambda_3$ ($\lambda_3 = 447$ nm)^[14]. In order to effectively make energy from the pump wave of ω_1 and ω_2 shift to the generation wave of ω_3 , in the process of sum frequency, it must satisfy the energy conservation and momentum conservation and we can obtain

$$\frac{hc}{\lambda_1} + \frac{hc}{\lambda_2} = \frac{hc}{\lambda_3},\tag{1}$$

where h is the Planck constant. Equation (1) means that a wavelength of λ_1 photon and a wavelength of λ_2 photon generate a wavelength of λ_3 photon. So the optimum proportion of pump power of 1341.4 nm and 670.7 nm in theory is

$$\frac{P_{1341.4}}{P_{670.7}} = \frac{hc/\lambda_1}{hc/\lambda_2} = \frac{1}{2}.$$
 (2)

Therefore, when a sub-cavity 670.7-nm pump source achieves the maximum power of 240 W, the corresponding injection power in the 1341.4-nm sub-cavity is 120 W by regulating pump source current. So oscillation optical gain in two sub-cavity can achieve similar. When the lengths of the 1341.4- and 670.7-nm sub-cavity



Fig. 3. Thermal-lens focal length of Nd:YAP rod at different pump powers.



Fig. 4. Fundamental mode radii in the centers of Nd:YAP rod versus thermal focal length. Inset shows beam trace in the KTP (from M3).

are 310 and 270 mm, respectively, Fig. 4 shows the fundamental mode radii in the centers of Nd:YAP rod changing with thermal-lens focal length. We can see from Fig. 4 that with the thermal-lens focal length changing, resonant cavity will go through two stabilization zone. When the fundamental mode spot becomes into infinite, it signes resonant cavity which changes from the stabilization zone into non-stabilization one. That is because the laser overflows the resonant cavity and resultes in higher diffraction loss. Figuer 3 shows that at the pump powers of 240 and 120 W, the thermal-lens focal length of Nd:YAP crystals are 180 and 430 mm, respectively. In this range the two sub-cavities are in the first stabilization zone, so the doubled cavity is a heat-stable cavity. ABCD beam transfer matrix is used to calculate the ray tracing in the sum-frequency crystal (from M3) and it is shown in the inset of Fig. 4. When the sum-frequency crystal KTP is placed at the 20-mm front of the output mirror M3, inside the sum-frequency crystal laser beam radius of fundamental frequency and frequency doubled are approximation equal to achieve a two-beam overlap better.

After 1079-, 1341.4-, and 670.7-nm lights were filtered, we used a PM100-19C type power meter of Coherent Company to measure the 447-nm laser's output power. Figure 5 shows the curve of the output power as a function of incident pump power on the Nd:YAP crystal in the sub-cavity of 1341.4 nm when the pump power on the Nd:YAP crystal in the sub-cavity of 670.7 nm was fixed at 240 W. In Fig. 5, we can see that the threshold power of laser was approximately 62 W. When the Nd:YAP crystal pump power injected into the sub-cavity of 1341.4 nm was 120 W, the highest output power of 5.7 W was obtained in 447 nm and continuing to increase the input power when the output power was reduced. This is because at this time the 1341.4-nm optical power density is larger than the one of 670.7 nm. The pump light of 1341.4 nm turned more to thermal, resulting in the thermal accumulation of crystal more serious. The gain of fundamental frequency laser and frequency doubled laser appeared mismatching. This basically corresponded with the theory analysis. If attemped to achieve higher output power, we should further improve the optical power density of 670.7 nm. We used a HR4000CG type fiber spectrometer of OCEAN OPTICS Company to measure the spectrogram, as shown in Fig. 6. The wavelength of blue laser is 447 nm, and there are not any other wavelength lasers. The output power fluctuation ΔP of the deep blue laser was tested at the incident pump power of 120 W with a time interval of 3 min in half an hour. If $\Delta \overline{P}$ was given by

$$\Delta \overline{P} = \sqrt{\sum_{i=1}^{n} \frac{\left(P_i - \overline{P}\right)^2}{n}},\tag{3}$$

the instability $\Delta \overline{P}/\overline{P}$ of the deep blue laser was better than 2%.

The deep blue laser spot and beam quality of the farfield were shown in Figs. 7 and 8, respectively. The maximum output power was 5.7 W, the average M^2 value was about 2.53 in both horizontal and vertical directions, measured by a Spiricon M^2 -200 Beam Quality Analyzer, and the laser output mode was similar to the distribution of TEM_{00} mode.

In summary, we have successfully demonstrated a deep



Fig. 5. Output power at 447-nm deep blue laser as a function of the incident pump power in Nd:YAP crystal.



Fig. 6. Spectrum of the blue laser.



Fig. 7. Far field of the 447-nm laser spots.



Fig. 8. Beam quality of the 447-nm laser (measured at 5.7-W output power).

blue laser at 447 nm with sum frequency in a type-II critical phase matching KTP crystal by using a doubly cavity and side-pumped two Nd:YAP crystal rods. When each Nd:YAP pump power is 240 and 120 W, the maximum output power of 5.7 W is obtained. The beam quality of the 447-nm laser is better and the power stability is better than 2%. The experimental results show that the intracavity sum-frequency-mixing by doubly resonant is an effective method for achieving high power blue laser.

This work was supported by the Education Department Foundation of Jilin Province under Grant No. 2007-36.

References

- Q. Shen, D. Xu, G. Qi, Q. Zhang, H. Hu, and J. Song, Optical Technique (in Chinese) **31**, 921 (2005).
- D. P. Pacheco, H. R. Aldag, D. E. Klimek, P. S. Rostler, and R. Scheps, in *Proceedings of the International Conference on Lasers* 376 (1990).
- 3. L. Marshall, Laser Focus World 40, (10)79 (2004).
- W. Liu, Y. Huo, and S. He, Acta Opt. Sin. (in Chinese) 22, 980 (2002).
- 5. Q. Zheng, L. Zhao, and S. Dong, Chinese J. Lasers (in

Chinese) **31**, 1030 (2004).

- F. Jia, Q. Xue, Q. Zheng, Y. Bu, and L. Qian, Appl. Phys. B 83, 245 (2006).
- Y. Lü, X. Zhang, Z. Yao, and F. Zhang, Chin. Opt. Lett. 5, 407 (2007).
- Y. Li, H. Tan, X. Fu, Y. Tian, B. Wang, and Y. Meng, Chinese J. Lasers (in Chinese) 35, 1308 (2008).
- H. Peng, W. Hou, Y. Chen, D. Cui, Z. Xu, C. Chen, F. Fan, and Y. Zhu, Opt. Express 14, 6543 (2006).
- H. Y. Shen, R. R. Zeng, Y. P. Zhou, G. F. Yu, C. H. Huang, Z. D. Zeng, W. J. Zhang, and Q. J. Ye, Appl. Phys. Lett. 56, 1937 (1990).
- 11. G. O. Boyd and D. A. Kleinman, SNLO, free software for modeling nonlinear frequency conversion processes in nonlinear crystals, http://www.sandia.gov/imrl/X1118/xxtal.htm.
- F. Song, C. Zhang, X. Ding, J. Xu, G. Zhang, M. Leigh, and N. Peyghambarian, Appl. Phys. Lett. 81, 2145 (2002).
- A. Geng, C. Zhao, Y. Bo, Y. Lu, and Z. Xu, Acta Phys. Sin. (in Chinese) 57, 6987 (2008).
- S. Shi, G. Chen, W. Zhao, and J. Liu, *Nonlinear Optics* (in Chinese) (Xi'an University Press, Xi'an, 2003).