All-solid-state 556 nm yellow-green laser generated by frequency doubling of a diode-pumped Nd:YAG laser

Zheng Quan,[1,2,*] Yao Yi,[1] Qu Dapeng,[2] Zhou Kai,[2] Liu Yang,[1] and Zhao Ling[1,2]

[1]*Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences,*
Changchun Jilin, 130033 China
[2]*Changchun New Industries Optoelectronics Tech. Co., Ltd., 130012 Changchun, China*
Corresponding author: pseudo-bear020121212@yahoo.com.cn

Received June 3, 2009; revised July 31, 2009; accepted August 21, 2009;
posted August 24, 2009 (Doc. ID 112177); published September 18, 2009

We demonstrate an efficient and compact yellow-green laser at 556 nm generated by intracavity frequency doubling of a continuous wave (CW) laser diode-pumped Nd:YAG laser at 1112 nm. An lithium triborate (LBO) crystal, cut for critical type I phase matching at room temperature, is used for second-harmonic generation (SHG) of the fundamental laser. With an incident pump power of 18 W, as high as 3.2 W of CW output power at 556 nm is achieved. The optical-to-optical conversion efficiency is as high as 17.8%, and the output power stability in 3 h is better than ±4.58%. To the best of our knowledge, this is the highest watt-level yellow-green laser generated by frequency doubling of a diode-pumped Nd:YAG laser at 1112 nm.

OCIS codes: 140.3580, 140.3480, 140.3515.

1. INTRODUCTION

Nd:YAG is a very superior material for diode-pumped high-power lasers due to its excellent thermal properties and output characteristics. Generally, a Nd:YAG laser operates at the most commonly used wavelengths of 1064 nm, 1319 nm, and 946 nm. However, the 1112 nm spectral line is an important Nd:YAG laser line and the second-harmonic generation (SHG) of this line is 556 nm, which has potential application in the areas of display, illumination, molecular biology, and chemistry. The 1112 nm and 1064 nm lines of Nd:YAG are both transitions from $^4F_{3/2}-^4I_{13/2}$ but with different Stark energy levels. In particular, the 1064 nm laser transition comes from R_2-Y_3 and 1112 nm from R_2-Y_6. The 1112 nm line must compete with the 1064 nm line, which has higher gain because the emission cross-section for 1112 nm is 1/15 of that for the 1064 nm line [1]. Consequently, efficient operation at 1112 nm requires the suppression of parasitic oscillation at 1064 nm, high pump intensity, and optimal resonator with low loss.

After Moore *et al.* had demonstrated a diode-pumped continuous wave (CW) Nd:YAG laser at 1123 nm with 1.7 W output power [2], Chen and Lan [3,4] and Guo and Chen [5] reported that the average output power of passively and actively acoustic-optical Q-switched diode-pumped 1123 nm Nd:YAG lasers is 150 mW and 3 W, respectively. The CW output of the 1123 nm laser has been enhanced to 2.6 W by Cai and Chen using a simple plano-concave resonator [6]. The 556 nm laser was first demonstrated by Jia and Chen, who obtained 102 mW output power, which they enhanced to 1.4 W in 2006 using a type-II KTP as the frequency-doubling crystal [7].

In this paper, a compact and high-power CW 556 nm yellow-green laser is demonstrated. The Nd:YAG laser crystal is pumped by a fiber-coupled laser-diode array, and a type I critical phase-matched lithium triborate (LBO) crystal plays the role of intracavity frequency doubling. With an incident pump power of 18 W, an up to 3.2 W556 nm yellow-green laser is achieved using a three-mirror folded resonator. The optical-to-optical conversion efficiency is as high as 17.8%, and the stability of the output power is better than 4.58%.

2. THEORY ANALYSIS

We comparing the performance of main laser transition lines in the Nd:YAG. In order to obtain laser oscillation of these lines at 1112 nm, where there is a lower gain cross-section than that of the other main laser lines, not only 1064 nm oscillation but also that at 1319 nm and the 946 nm must be suppressed at the same time. Generally, the left side of the Nd:YAG is coated at 946 nm and 1319 nm antireflection to suppress the oscillation of the two laser lines, and the output coupler is coated at 1064 nm antireflection to restrain the oscillation at 1064 nm. This method brings inconvenience to the coating progress and is not advantagageous to commercial utilities even though the 1112 nm laser could be obtained. In our experiment the output coupler is coated at 1064 nm, 946 nm, and 1319 nm antireflection, and the suppression of the three chief laser lines is accomplished by one cavity mirror. The left side of the Nd:YAG is antireflection (AR) coated at 808 nm and high-reflection (HR) coated at 946, 1064, 1112, and 1319 nm. The output coupler is AR coated at the three main laser lines such as 1064, 1319, and 946 nm, and the SHG laser at 556 nm but highly reflecting at

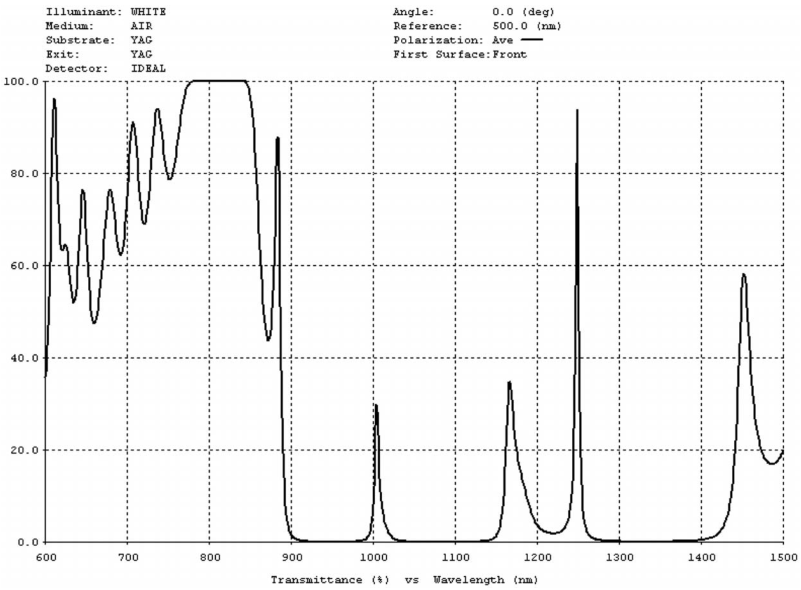

Fig. 1. Transmissivity of the left side of the Nd:YAG crystal.

1112 nm. Figures 1 and 2 are the coating curves of the left side of the Nd:YAG crystal and the concave surface of the output coupler. However, it is difficult to achieve SHG discrimination of 1112 nm and 1123 nm by traditional film design. A thick etalon could be inserted into the cavity to suppress the oscillation of one fundamental wavelength. Although the etalon acts as a line selector, a large insertion loss is a disadvantage in the attempt to increase output power.

A nonlinear crystal such as potassium titanly phosphate (KTP) and LBO is always used in SHG. As shown in a comparison of the characteristics of the two crystals in Table 1, although the effective nonlinear optical coefficient of KTP is 3.69 pm/V, which is much larger than that of LBO at 0.83 pm/V, the walk-off angle of LBO is 4.62 mrad, which is much smaller than that of KTP at 25.53 mrad. An LBO crystal with longer length could be used to obtain higher SHG efficiency. Owing to the characteristic of KTP, high intracavity power will incur a gray trace that makes the output power of the harmonic wave unstable or even decrease for a long time. Therefore LBO is selected to be the frequency-doubling crystal.

3. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 3. The pump source is a 20 W fiber-coupled laser diode (LD) array with emission wavelength of 808.5 nm. The core diameter of the coupling fiber is 400 μm, and its numerical aperture is 0.22. The emission central wavelength of the pump source can be tuned by changing the temperature of the heat sink to match the best absorption of the laser crystal. The

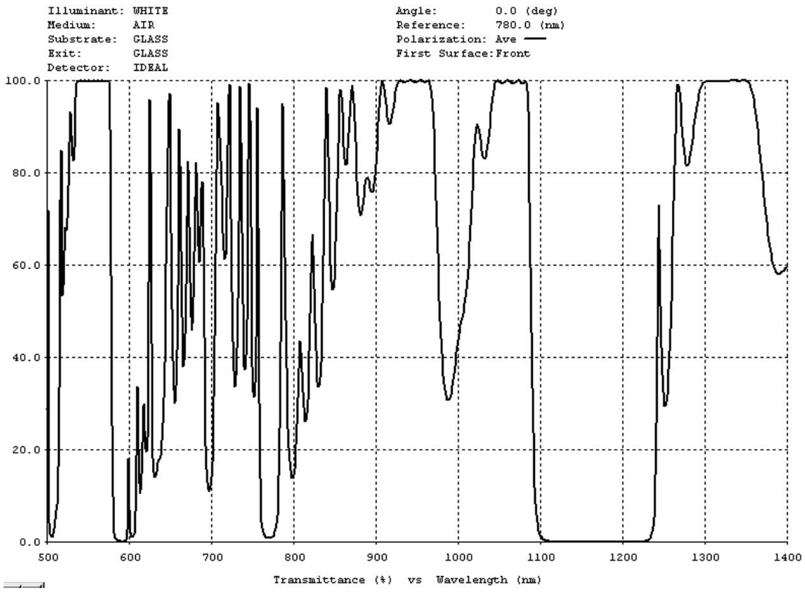

Fig. 2. Transmissivity of the output coupler of the 556 nm laser.

Table 1. Comparison of the Frequency-Doubling Parameters of KTP and LBO

Crystal	Phase-matching type	d_{eff} (pm/V)	Accept Angle	Walk-Off-Angle
KTP	1123(o) + 1123(e) = 561(o)	3.69	2.41 mrad* cm	25.53 mrad
LBO	1123(o) + 1123(o) = 561(e)	0.836	15.15 mrad* cm	4.62 mrad

optics coupling system is composed of two plano-convex lenses that are antireflection coated at 808.5 nm. The pump beam is imaged into the crystal at a ratio of 1:1. The laser crystal is a 1.0% at.% Nd^{3+} doped, $3\times3\times5$ mm^3 Nd:YAG crystal that is wrapped with indium foil and mounted on a thermal electronic cooled cooper block to keep the temperature at 20°C.

The relative performance of the 1112 nm line is half that of the 1064 nm line, and its emission cross-section is much smaller than that of the main spectral lines of Nd:YAG. To obtain the oscillation of 1112 nm, the three chief lines at 1064 nm, 1319 nm, and 946 nm should be suppressed [8]. The left facet of the Nd:YAG is the input coupler with 808 nm antireflection coated and 946 nm, 1064 nm, 1319 nm, and 1112 nm high reflection. The other facet of the Nd:YAG is antireflection coated at 1112 nm, 946 nm, 1064 nm, and 1319 nm. M_1 is a 50 mm radius-of-curvature plano-concave output mirror. The concave facet is antireflection coated at 1064 nm, 946 nm, 1319 nm, and 556 nm and high-reflection coated at 1112 nm. The plano facet of M_1 is antireflection coated at 556 nm. The end mirror M_2 is a 200 mm radius-of-curvature concave mirror high-reflection coated at 1112 nm and 556 nm. LBO is a frequency doubler with dimensions $2\times2\times10$ mm^3, cut for critical type I phase matching ($\theta = 90°$, $\varphi = 8.4°$) and antireflection coated at 1112 nm and 556 nm on both sides to reduce the intracavity loss of fundamental laser and the yellow-green laser.

The resonator is a three-mirror folded cavity with two separate waists. One is near the left side of Nd:YAG to satisfy the mode-matching condition. The other is near the surface of M_2, which could enhance the efficiency of SHG. The lengths of cavity arms L_1 and L_2 are about 70 mm and 40 mm, respectively. After numerical calculaton, the radii of the beam waists are 150 μm and 60 μm, which satisfy the design requirement.

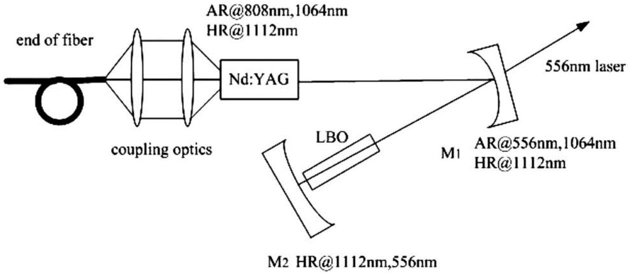

Fig. 3. Schematic of the intracavity frequency doubling of the Nd:YAG/LBO crystal at 556 nm.

4. RESULTS AND DISCUSSIONS

When tuning the temperature control of the pump source and aligning each component to a good state, the color of the fluorescence in the Nd:YAG is blue owing to the excited-state absorption (ESA) of the upper laser level. Although the Nd:YAG is isotropic, the frequency-doubling LBO crystal and the LD with high polarization ratio create a fundamental wave with high polarization, and it is not necessary to insert a polarizer such as a

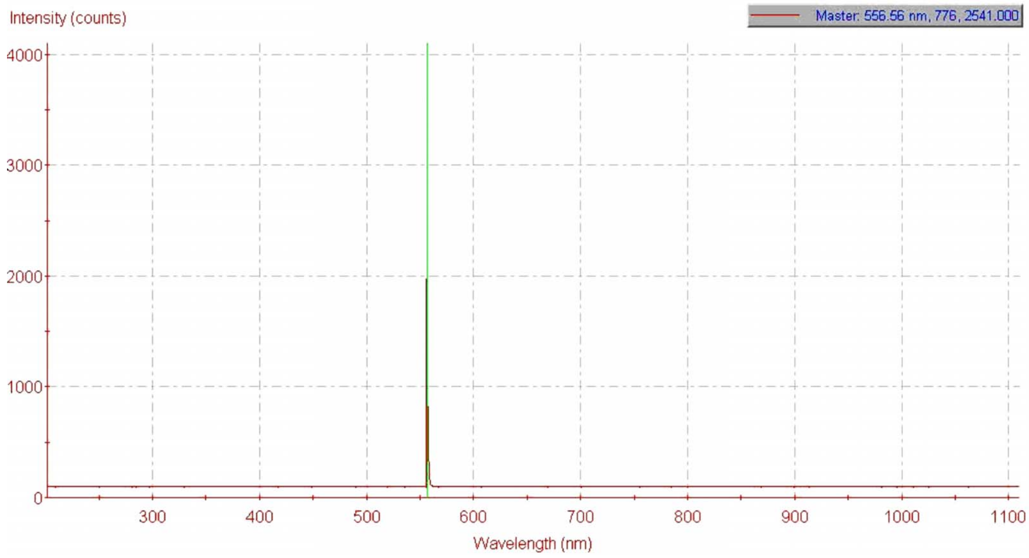

Fig. 4. (Color online) Spectral of the 556 nm yellow-green laser.

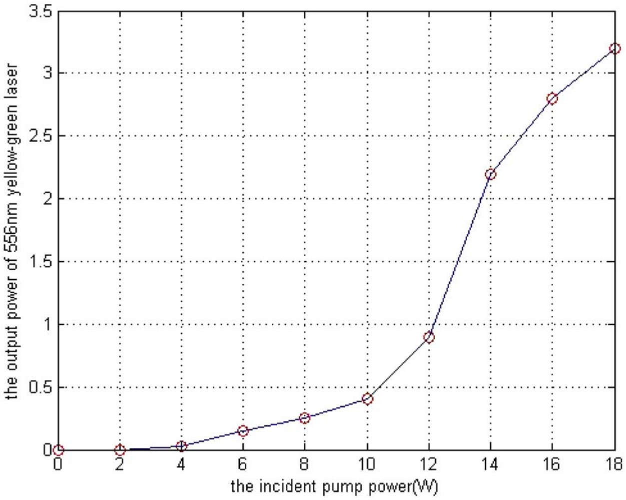

Fig. 5. (Color online) Output power at 556 nm versus incident pump power.

Fig. 6. (Color online) Beam spot of the 556 nm yellow-green laser.

Brewster plate into the cavity. When the LBO is inserted into the cavity close to the end mirror M_2 and the aligning angle of the LBO is tuned, the maximal output power of 3.2 W at 556 nm is achieved.

Using the LABRAM-UV spectrum analyzer to scan the SHG laser and dealing with the data by software, the spectrum of the SHG laser is shown in Fig. 4. The dependence of the output power at 556 nm on the incident pump power is shown in Fig. 5. The output power is 3.2 W at 556 nm, and the incident pump power is 18 W.

The output power fluctuation is due to the spectral line competition between the 1112 nm line and the 1123 nm line. When inserting an LBO cut for a 1112 nm SHG laser into the cavity, the output at 556 nm could be considered as the loss of the 1112 nm fundamental wave. The loss of the 1112 nm line increases the net gain of the 1123 nm line, which leads to an increase of the intracavity power at 1123 nm. This competition progress decreases the loss of the 1112 nm line, which equals the net gain at 1112 nm. Thus the power of the second harmonic wave increases. The output power fluctuation is due to this process. The beam spot of the 556 nm laser is shown in Fig. 6. Figure 7 is the beam quality testing result, which shows that the 556 nm laser is operating at near TEM_{00} mode and the far-field intensity distribution is near Gaussian distribution. The M-square factor is about 1.7 measured by the knife-edge method with a Spiricon Beam star FX.

5. CONCLUSIONS

An efficient and compact LD-pumped yellow-green laser has been demonstrated by using a Nd:YAG laser and LBO crystals as the gain medium and a nonlinear crystal for intracavity frequency doubling, respectively. A compact three-mirror folded cavity is employed to enhance conversion efficiency. With an incident pump power of 18 W, the maximal output power at 556 nm can be as high as 3.2 W. The optical-to-optical conversion efficiency is higher than 17.8%, and the stability of the output power is better than 4.58% in 3 h.

ACKNOWLEDGMENTS

This work is supported by Changchun New Industries Optoelectronics Tech. Co. Ltd (www.cnilaser.com).

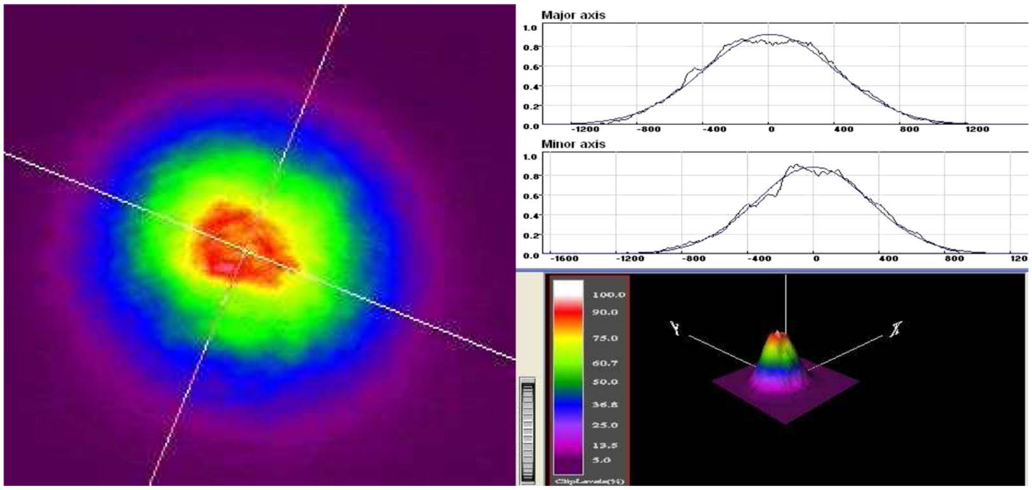

Fig. 7. (Color online) Beam profile of the 556 nm yellow-green laser.

REFERENCES

1. S. Singh, R. G. Smith, and L. G. Van Uiter, "Stimulated-emission cross section and fluorescent quantum efficiency of Nd^{3+} in yttrium aluminum garnet at room temperature," Phys. Rev. B **10**, 2566–2572 (1974).
2. N. Moore and W. A. Clarkson, "Efficient operation of a diode-bar-pumped Nd:YAG laser on the low-gain 1123 nm line," Appl. Opt. **38**, 5761–5764 (1999).
3. Y. F. Chen and Y. P. Lan, "High-power diode-pumped actively Q-switched Nd:YAG laser at 1123 nm," Opt. Commun. **234**, 309–313 (2004).
4. Y. F. Chen and Y. P. Lan, "Diode-pumped passively Q-switched Nd:YAG laser at 1123 nm," Appl. Phys. B: Photophys. Laser Chem. **79**, 29–31 (2004).
5. X. Guo and M. Chen, "Diode-pumped 1123 nm Nd:YAG laser," Chin. Opt. Lett. **2**, 402–404 (2004).
6. Z. Cai and M. Chen, "Diode end-pumped 1123 nm Nd:YAG laser with 2.6 W output power," Chin. Opt. Lett. **3**, 281–282 (2005).
7. F. Jia and Q. Zheng, "Yellow light generation by frequency doubling of a diode-pumped Nd:YAG laser," Opt. Commun. **259**, 212–215 (2006).
8. W. Koechner, *Solid State Laser Engineering* (Science Press, Beijing, 2002).