ISSN 1054-660X, Laser Physics, 2008, Vol. 18, No. 1, pp. 15–17.

Intracavity Frequency Doubling with a Yb:YAG/LBO Laser at 515 nm

T. Yubing[a, b, *], **T. Huiming**[a], **C. Hongzhong**[a, b], **and M. Jieguang**[a, b]

[a] *Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Jilin, 130033 China*

[b] *Graduate School of the Chinese Academy of Sciences, Beijing, 100080 China*

*e-mail: tianyb761@hotmail.com

Received August 1, 2007

Abstract—We, for the first time, report the intracavity frequency doubling at 1030 nm in an LBO nonlinear optical crystal, at a type-I phase-matching direction of (θ, Φ) = (90°, 13.6°), performed with a double-LD polarization coupled system. With an incident power of 2 W, the maximum output power of 5.62 mW at 515 nm was obtained using a $2 \times 2 \times 10$ mm^3 LBO crystal. The threshold was 726 mW. The optical conversion efficiency was 0.28%.

PACS numbers: 42.55.Xi, 42.60.By, 42.65.Ky, 42.70.Mp

DOI: 10.1134/S1054660X08010039

1. INTRODUCTION

The Diode-pumped Yb:YAG laser has attracted attention as a high power and high efficiency laser due to its robust properties. Yb:YAG has a long storage lifetime (951 μs) [1] and a very low quantum defect (8.6%), resulting in three times less heat generation during lasing than Nd-based laser systems [2]. Moreover, Yb:YAG has no undesirable loss processes, such as excited-state absorption, up conversion, and concentration quenching owing to its simple electrical structure. The absorption bandwidth at 940 nm is 18 nm, which makes it less sensitive to diode wavelength specifications. Thus, this material is highly suitable for diode pumping.

The Yb:YAG intracavity frequency doubling is resonant with I_2 absorption lines in the 515 nm region [3, 4], some of which have five-times narrower natural line widths than those in the 532-nm region by small Frank–Condon factors. Thus, it is promising to establish highly accurate frequency standards with a compact I_2 cell. Another interest in the Yb:YAG laser is that the wavelength of 515 nm matches the highest power line of Ar-ion lasers, thereby leading to the possibility of an Ar-ion laser and its applications being replaced by frequency-doubled Yb:YAG lasers [5].

In the past decade, end-, face-, edge-, and side-pumped systems have been demonstrated with high efficiencies and high average output powers [5–11]. But, they all focused on 1030 nm with high-power laser diodes. As to 2-W LD, we have not found any reports on 515 nm in diode-pumped Yb:YAG lasers.

In this letter, type-I CPM (critical phase-matching) LBO was used for 1030-nm intracavity frequency doubling. By reasonable design, a 5.62-mW 515-nm green laser was obtained in an end-pumped Yb:YAG laser with a flat-concave resonator.

2. CHARACTERISTICS OF CPM LBO FOR 1030-nm FREQUENCY DOUBLING

We have calculated some important parameters of different CPM crystals. They are listed in Table 1. It is shown that, although LBO has a relatively lower $d_{\rm eff}$ than KTP, its small walk-off and large acceptance angles can make the effective work length (L) of LBO very long for 1030-nm frequency-doubling. Based on the formula [12]

$$L = 1.16\omega/\rho, \qquad (1)$$

we can calculate the length L, where ω is the radius of the fundamental wave beam through the LBO. Formula (1) has shown that, when ρ is very small, lowering ω can

Table 1. Comparison of the three different CPM crystals for the 1030–515 nm conversion

Items CPM	Process (1030–515 nm)	CPM angle (θ, Φ)	$d_{\rm eff}$, pm/V	Walk-off angle ρ, mrad	Acceptance, mrad m	L, mm
LBO (I)	o+o—e	90°, 13.6°	0.828	8.16	7.86	14.2
LBO (II)	o+e—o	25.4°, 90°	0.610	7.21	8.97	16.1
KTP (II)	o+e—o	75.6°, 90°	1.90	22.93	2.46	5.1

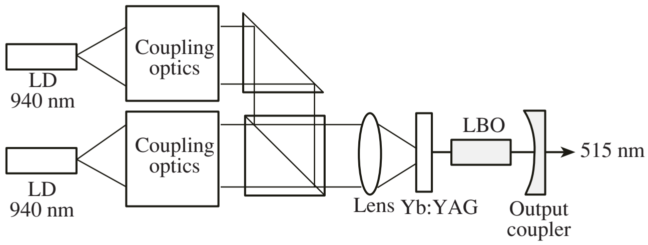

Fig. 1. Schematic of an LD-pumped Yb:YAG crystal.

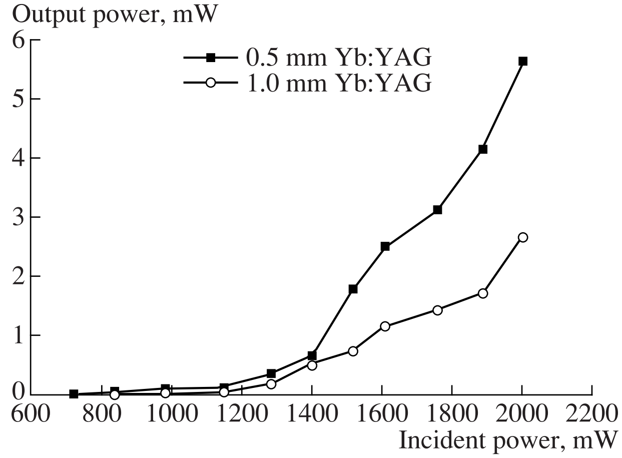

Fig. 2. The output power of the green light at 515 nm as a function of the pump power.

also have a large L. In the meantime, lowering ω can increase the doubling efficiency by increasing the power intensity of the fundamental wave through the LBO. Although they have the equivalent doubling efficiency on 1030 nm, in theory by employing different lengths of two nonlinear optical crystals, the acceptance bandwidth in the LBO is about seven times wider than in KTP, and the LBO crystal has a higher transmission than KTP at the wavelength of 515 nm, so we employed a $2 \times 2 \times 10$ mm^3 LBO crystal.

3. EXPERIMENTAL SETUP

The laser experimental setup is shown in Fig. 1. In order to increase the pump intensity, a double-LD polarization-coupled system was employed in the experiment. The diodes were mounted on a copper block cooled by a thermoelectric cooler (TEC). The maximum output power of each laser diode was 2 W. Their center wavelength is 940 nm at 23°C. Light emitted from the LD was reshaped to high-quality pumping light after going through the coupling optics and then was focused into the laser crystal by a focus lens. The pump-spot radius in the laser crystal is 100 μm. The coupling optics lens is not coated for 940 nm, and the coupling efficiency is only 50%. The $2 \times 2 \times 10$ mm^3 LBO crystal was employed, both sides of which were antireflection (AR) coated at 515/1030 nm ($R < 0.2\%$). The radius of curvature of the output coupler is 50 mm. It was high reflection (HR) coated at 1030 nm (R = 99.8%), antireflection (AR) at 515 nm ($T > 95\%$), and the plane face was AR coated at 1030 and 515 nm ($T >$ 98%). The cavity length was approximately 25 mm. In the experiment, two types of Yb:YAG crystals were used to study the performance of the Yb laser. Their parameters are presented in Table 2. The Yb:YAG crystal is wrapped by a thin indium foil and then attached to the copper heat sink to obtain a good thermal contact and stress relief.

4. RESULTS AND DISCUSSIONS

The output power of the green light at 515 nm as a function of pump power is shown in Fig. 2. Before measuring the output power, 940 and 1030 nm light were filtered out. The results show that the threshold of the pump power was 726 and 839 mW for a 0.5-mm-thick Yb:YAG and 1-mm-thick Yb:YAG, respectively. When the incident power is 2 W, 5.62 and 2.66 mW output power at 515 nm were obtained for the two crystals. There is no saturation appearing. Their optical conversion efficiency was 0.28 and 0.13%, respectively.

In the end-pumped Yb:YAG lasers, there is reabsorption at the laser wavelength that is due to the population in the lower laser level. Figure 3 shows the schematic of gain and reabsorption loss. When the crystal length increases, the fraction of the pump power absorbed increases, but the reabsorption loss also increases. Hence, there is an optimum crystal length L_{ab}, at which the gain is equal to the reabsorption loss as shown in Fig. 3. For 10 at % Yb^{3+} doped YAG crystal, the absorption coefficient $\alpha = 10$ cm^{-1} and the absorption depth is 1.0 mm [14]. Thus, the optimum crystal length is lower than 1.0 mm. The length of a 0.5-mm-

Table 2. Experimental parameters of the Yb: YAG crystals used in this paper

Sample	Concentration of Yb, at %	Dimension (diameter × length, mm)	Coating
1	10	3.0 × 0.5	S1: HR 1030 and 515 nm; HT: 940 nm; S2: AR 1030 and 515 nm
2	10	4 × 1	S1: HR 1030 and 515 nm; HT: 940 nm; S2: AR 1030 and 515 nm

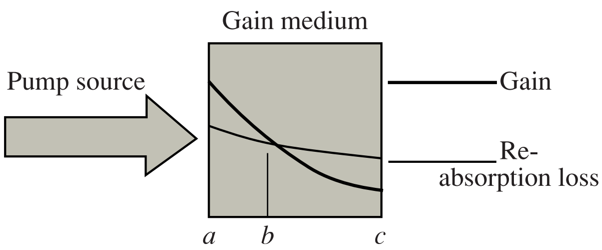

Fig. 3. Schematic of the gain and reabsorption loss in Yb:YAG.

thick Yb:YAG crystal approximates the optimum crystal length. Hence, its threshold is lower and the output power is higher than those of 1-mm-thick Yb:YAG.

5. CONCLUSIONS

In this paper, we have reported an intracavity frequency doubling at 1030 nm in a nonlinear optical crystal of LBO, performed with a double-LD polarization-coupled system. According to rational phase-matching, a CW output power at 515 nm of 5.62 mW has been obtained with an optical conversion efficiency of 0.28% at the incident pump power of 2 W. Highly efficient 515-nm output should be achieved by improving the coating quality and reducing the pump beam radius on the crystal.

REFERENCES

1. D. S. Sumida and T. Y. Fan, "Effect of Radiation Trapping on Fluorescence Lifetime and Emission Cross Section Measurements in Solid State Laser Media," Opt. Lett. **19**, 1343–1345 (1994).
2. T. Y. Fan, "Heat Generation in Nd:YAG and Yb:YAG," IEEE J. Quantum Electron. **29**, 1457–1459 (1993).
3. A. N. Goncharov, M. N. Skvortsov, and V. P. Chebotayev, "Study of Relaxation of Molecular-Iodine by the Method of Saturated Absorption-Spectroscopy," Appl. Phys. B **51**, 108–115 (1990).
4. Jiro Saikawa, Sunao Kurimura, and Ichiro Shoji, "Tunable Frequency-Doubled Yb:YAG Microchip Lasers," Opt. Mater. **19**, 169–174 (2002).
5. C. Bibeau, R. J. Beach, S. C. Mitchell, et al., "High-Average-Power 1-μm Performance and Frequency Conversion of a Diode-End-Pumped Yb:YAG Laser," IEEE J. Quantum Electron. **34**, 2010–2019 (1998).
6. R. J. Beach, "cw Theory of Quasithree Level End-Pumped Laser Oscillators," Opt. Commun. **123**, 385–393 (1996).
7. T. Y. Fan, S. Klunk, and G. Henein, "Diode-Pumped Q-Switched Yb:YAG Laser," Opt. Lett. **18**, 423–425 (1993).
8. P. Lacovara, H. K. Choi, C. A. Wang, et al., "Room-Temperature Diode-Pumped Yb:YAG Laser," Opt. Lett. **16**, 1089–1091 (1991).
9. E. C. Honea, R. J. Beach, S. C. Mitchell, et al., "High-Power Dual-Rod Yb:YAG Laser," Opt. Lett. **25**, 805–807 (2000).
10. T. S. Rutherford, W. M. Tulloch, E. K. Gustafson, and R. L. Byer, "Edge-Pumped Quasithree-Level Slab Lasers: Design and Power Scaling," IEEE J. Quantum Electron. **36**, 205–219 (2000).
11. H. W. Bruesselbach, D. S. Sumida, R. A. Reeder, and R. W. Byren, "Low-Heat High-Power Scaling Using InGaAs-Diode-Pumped Yb:YAG Lasers," IEEE J. Select. Top. Quantum Electron. **3**, 105–116 (1997).
12. Jean-Jacques Zondy, Mohamed Abed, Salah Khodja, "Twin-Crystal Walk-off-Compensated Type-II Second-Harmonic Generation: Single-Pass and Cavity-Enhanced Experiment in KTP," J. Opt. Soc. Am. B **11**, 2368–2379 (1994).
13. T. Taira, W. M. Tulloch, and R. L. Byer, "Modeling of Quisi-Three-Level Lasers and Operation of cw Yb:YAG Lasers," Appl. Opt. **36**, 1867–1874 (1997).
14. Y. Kalisky, C. Labbe, K. Waichuman, "Passively Q-Switched Diode-Pumped Yb:YAG Laser Using Cr^{4+} Doped Garnets," Opt. Mater. **19**, 403–413 (2002).