ISSN 1054-660X, Laser Physics, 2007, Vol. 17, No. 12, pp. 1345–1348.

Efficient Generation of a CW 593.5-nm Laser by Intracavity Sum-Frequency Mixing with a BiB_3O_6 (BIBO) Crystal

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Received June 8, 2007

Abstract—A compact, efficient yellow-orange light at 593.5 nm was realized by the intracavity sum-frequency mixing using a BIBO crystal in a diode-pumped Nd:YVO_4 laser. At an incident pump power of 3.5 W, up to 126 mW of CW output light at 593.5 nm was achieved with a 1.5-mm-long critical phase-matching BIBO. The optical-to-optical conversion efficiency was up to 3.6%, which was comparable to a 5-mm-long LBO. The beam equality was excellent with an ellipticity of 0.97 and output noise of less than 0.8% (rms). Results confirm that the BIBO is an efficient material for frequency conversion in the visible region.

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

DOI: 10.1134/S1054660X07120018

1. INTRODUCTION

In recent years, lasers in the yellow spectral region (560–620 nm) have attracted increased attention due to their advantages in the field of medicine, biology, display, and so on. One efficient approach to generating light in this spectral region is to use intracavity sum-frequency mixing (SFM). Several papers have been published towards the realization of the yellow-orange light of 593.5 nm through a SFM of 1064 and 1342 nm in a Nd:YVO_4 crystal [1–6]. The crystals commonly used for nonlinear frequency conversion in the visible region are BBO, LBO, and KTP. Although these crystals show good nonlinear properties, they still suffer from some drawbacks. For example, KTP and BBO have a large effective nonlinear coefficient (d_{eff}), but they suffer from a large walk-off angle, which is unfavorable for a circular light spot and limits the interaction length of the light. Also, it was reported that the SFM output at 593.5 nm using a KTP crystal can be noisy due to type-II phase matching [3]. The LBO could generate a high quality beam with low noise [5], but it is hygroscopic. Also, due to the small value of the d_{eff}, a longer crystal was required in order to obtain a high conversion efficiency. Therefore, it is desirable to develop a better NLO material that can mitigate these limitations.

BiB_3O_6 (BIBO) is a new nonlinear material with unique optical properties for frequency conversion in the visible and UV regions. The effective nonlinear coefficient of BIBO was reported to be larger than those of BBO and LBO, and comparable to KTP [7, 8]. Also, BIBO is nonhygroscopy and has a high optical-damage threshold [8]. Such a combination of properties makes BIBO an attractive nonlinear material for frequency conversion application. Thus far, a number of frequency conversion experiments have been performed, but mainly on the generation of green, red, and blue lasers through SHG.

Here, we report the results of intracavity SFM at 593.5 nm using a BIBO crystal. Through optimizing the reflectivity of the output mirror, a dual-wavelength operation of 1064 and 1342 nm was achieved in a simple linear cavity. After a 1.5-mm-long BIBO was inserted into the cavity, 126 mW of 593.5-nm yellow-orange light with excellent beam equality was obtained with an incident pump power of 3.5 W.

2. PHASE-MATCHING PROPERTIES OF BIBO

With the Sellmeier equation of BIBO presented in [8], the type-I critical phase-matching curve for sum-frequency mixing at the fundamental wavelengths of 1064 and 1342 nm was calculated as shown in Fig. 1. The maximum value of d_{eff} (2.25 pm/V) was found to be at the orientation of $(\theta, \varphi) = (3.3°, 0°)$. Therefore, the BIBO crystal used in the SFM experiment was cut for this direction, with the dimensions $2.0 \times 2.0 \times 1.5$ mm^3.

Using the SNLO software, the nonlinear properties of the BIBO for the SFM are listed in the table. For comparison, the corresponding parameters of the LBO and KTP are also listed. From the table, the d_{eff} of BIBO is 2.7 times higher than that of the LBO and the walk-off angle of the BIBO is 1/2 of KTP. Thus, for its compactness and efficiency, the BIBO is considered as the better material for the nonlinear process.

3. EXPERIMENTAL SETUP

Figure 2 shows the experimental setup. A linear resonator with a length of 22 mm was employed to make

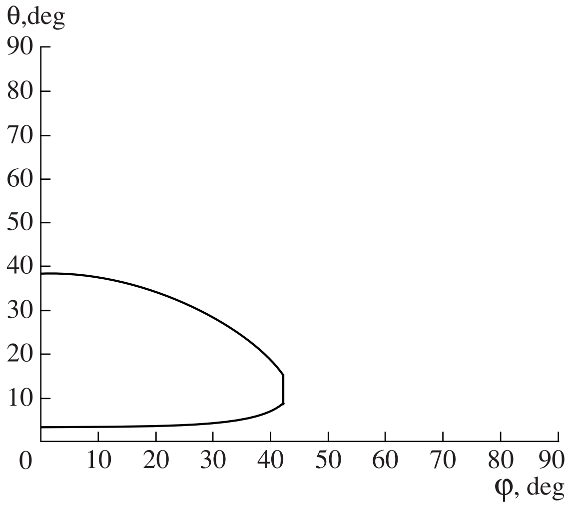

Fig. 1. Phase-matching curve of the BIBO.

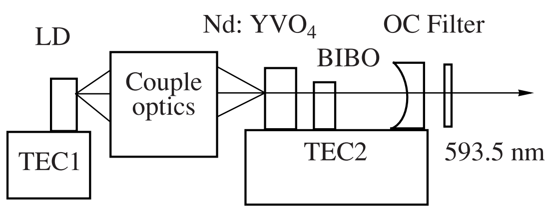

Fig. 2. Scheme of the intracavity SFM 593.5-nm laser.

the system very simple and compact. The pump source was a laser diode supplied by LASERTEL with a maximum output power of 5 W and a central emission wavelength of 808.9 nm. The pump light was reshaped to a high quality (with an ellipticity of 0.91 and a beam waist radius of about 85 μm) and injected into the laser crystal. An a-cut Nd:YVO_4 crystal with a Nd^{3+} concentration of 1.0 at % and the dimensions $3 \times 3 \times 2$ mm^3 was employed as the gain medium. For simplicity and a reduction of cavity loss, the pump face of the Nd:YVO_4 crystal was coated to be antireflection (AR) at 808 nm ($T > 95\%$) and high reflection (HR) at 1064 and 1342 nm ($R > 99.9\%$) acting as a one-end mirror of the resonator. The other face of the crystal was coated to be AR at both the 1064- and 1342-nm wavelengths. The remaining reflection was as small as possible to suppress the effect of the F–P etalon. A $2.0 \times 2.0 \times 1.5$-mm^3 BIBO, cut for type-I phase matching ($\theta = 3.3°$, $\varphi = 0°$) for the SFM of 1064 and 1342 nm, was used as the nonlinear crystal. Both ends of the crystal were AR coated at 1064.0, 1342.0, and 593.5 nm to reduce the reflection losses in the cavity. To remove the heat generated by the absorption and sum-frequency mixing process, the Nd:YVO_4 and BIBO crystal were wrapped in indium foil, mounted in a copper block, and cooled using a thermal electronic cooler (TEC).

The output coupler (OC) was a concave mirror with 50-mm radius of curvature. For Nd:YVO_4 crystal, the ratio of the stimulated emission cross section between the $^4F_{3/2} - {}^4I_{11/2}$ (1064 nm) and $^4F_{3/2} - {}^4I_{13/2}$ transitions (1342 nm) is about 3.3. Thus, in order to balance the gain competition and obtain the optimum fundamental dual-wavelength operation, the left facet of the OC was coated to be HR at 1342 nm ($R > 99.9\%$), partial transmission at 1064 nm ($T = 1\%$), and HT at 593.5 nm as described in [4]. The right facet of the OC was HT coated at 593.5 nm.

4. RESULTS AND DISCUSSION

The spot of the pump light in the Nd:YVO_4 was about 85 μm. With a cavity length of 22 and a 50-mm radius of curvature of the OC, the spot radius of the oscillating light in the laser crystal was calculated to be about 93 μm for 1064 nm and 100 μm for 1342 nm using the ABCD matrix. Thus, the efficient mode match between the pump light and oscillating light was achieved [9]. Also, a larger spot radius of 1342 nm compared to that of 1064 nm can make up for the relatively small stimulated-emission cross section for the 1342-nm transition and contribute to the dual-wavelength operation to some extent.

Without the BIBO, the threshold pump power for the fundamental lights was about 500 mW. Then, the BIBO was inserted into the resonator and the yellow-orange light was generated by increasing the current on the LD.

After aligning each component to a good state and carefully turning the output coupler, a maximum output power of 126 mW was obtained at the pump power of 3.5 W. Figure 3 shows the dependence of the yellow-

Properties of BIBO, LBO, and KTP for SFM at 1064 and 1342 nm

Crystals	BIBO	LBO	KTP
Phase matching	1342(o) + 1064(o) = 593.5(e)	1342(o) + 1064(o) = 593.5(e)	1342(e) + 1064(o) = 593.5(o)
(θ, φ), deg	3.3, 0	90.0, 2.6	78.0, 0
d_{eff}, (pm/V)	2.25	0.837	3.69
Walk-off angle, mrad	0, 0, 9.71	0, 0, 1.58	20.79, 0, 0
Angle tolerance, (mrad cm)	3.43	23.37	3.55

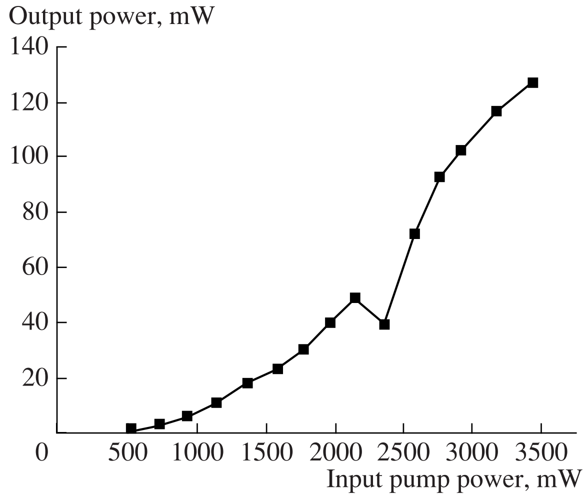

Fig. 3. Output power at 593.5 nm as a function of the incident pump power.

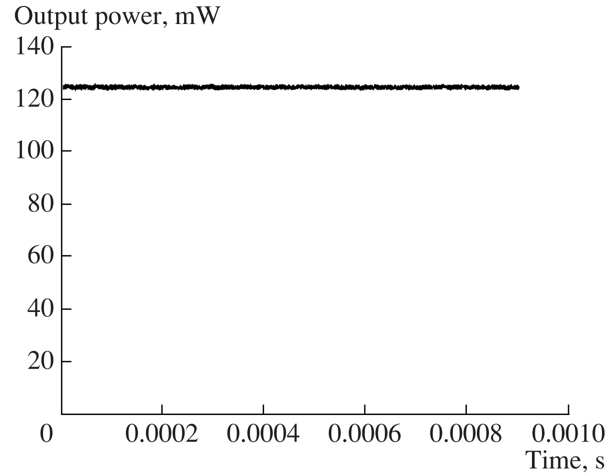

Fig. 4. The noise characteristic of the output at 593.5 nm.

orange output power on the incident pump power. The total light-to-light conversion efficiency was 3.6%. Noticeably, in Fig. 3, there is a break around the pump power of 2.4 W. Then, the output power increases sharply. As the dual-wavelength operation is found to be very sensitive to the loss and gain modulation [10], we believe that the break is mainly caused by the change in the relative gains for the fundamental 1064 and 1342 nm due to an increase in the pump power.

To investigate the noise characteristic of the yellow-orange light, the laser output with BIBO was monitored by a fast Si photodiode and recorded by a digital oscilloscope (LeCroy 9361C). As shown in Fig. 4, the output light showed quite a low noisy behavior over a very short time scale with the output noise calculated to be 0.8% (rms).

The beam equality of the yellow-orange light was also measured using a beam profiler (Model 2350, Photon Inc.). As shown in Fig. 5, the beam was in the TEM_{00} mode with an ellipticity of 0.97.

For comparison, a different result was recorded by replacing the BIBO crystal with a 5-mm-long LBO. A maximum output power of 130 mW was obtained at a 3.5-W pump power. From the results, the conversion efficiency of the 1.5-mm-long BIBO is comparable to that of the 5-mm-long LBO. With a walk-off angle of 9.71 mrad and beam radius of about 100 μm, the maximum interaction length of BIBO for the SFM was calculated to be 11 mm. Thus, we believe that, with a longer BIBO, the conversion efficiency will be further increased.

5. CONCLUSIONS

In summary, we have demonstrated a CW diode-pumped $Nd:YVO_4$ laser operating at 593.5 nm in a lin-

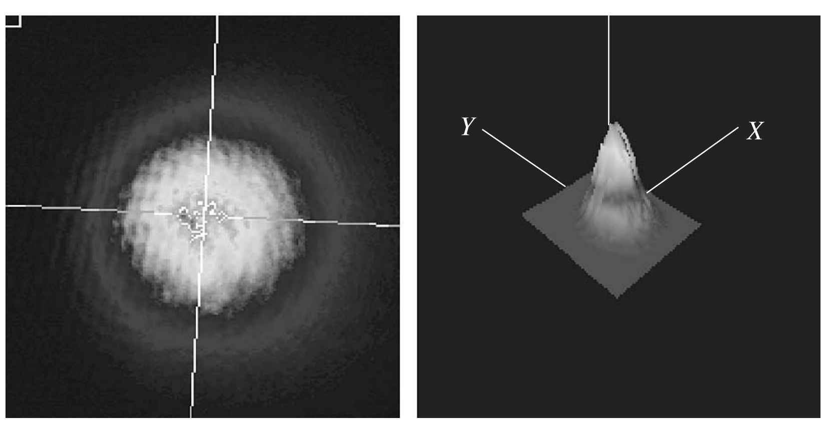

Fig. 5. The beam shape of the yellow output.

ear cavity. Employing a BIBO crystal for type-I critical-phase matching, as much as a 126-mW yellow-orange light at 593.5 nm was generated under the 3.5-W pump power with an optical conversion efficiency of 3.6%. The beam equality was excellent with an ellipticity of 0.97 and output noise of less than 0.8%. The laser is simple in structure and efficient in output. Thus, it favors the realization of 593.5-nm yellow-orange laser products.

ACKNOWLEDGMENTS

We acknowledge the support of the Changchun New Industries Optoelectronics Co., Ltd. (CNI). This work was also supported by the National High-Tech 863 Plan of the People's Republic of China (no. 2002AA311140).

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