High-Efficiency Second Harmonic Generation of Mode-Locked Picosecond Ti:sapphire Laser Using BiB_3O_6 Crystal with External Enhancement Cavity

Yuma Takida, Tatsuya Ohira, Shingo Maeda, and Hiroshi Kumagai

Graduate School of Engineering, Osaka City University, 3-3-138 Sugimoto, Sumiyoshi-ku, Osaka-shi, Osaka 558-8585, Japan
y.takida@a-phys.eng.osaka-cu.ac.jp

We reported a high-efficiency second harmonic generation (SHG) of a low-power mode-locked picosecond Ti:sapphire laser, whose average output power was less than 1 W, using a BiB_3O_6 (BiBO) nonlinear crystal installed in an external enhancement cavity. Ultraviolet (UV) coherent light at 389 nm with the maximum average power of 506 mW was obtained with the input average power of 805 mW using the external cavity. Considering the reflective loss of the output coupler of the 389-nm light, we could estimate the intrinsic conversion efficiency of 70%. This value, to the best of our knowledge, is the highest conversion efficiency for SHG using a BiBO crystal, even at the relatively low fundamental power.

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1. Introduction

Ultraviolet (UV) coherent light sources have received remarkable attention from various applications including laser processing, lithography, and spectroscopy. Second harmonic generation (SHG) of solid-state infrared (IR) laser in optical nonlinear crystals is widely used for the development of high-power stable UV coherent light sources. For frequency conversion in UV spectral region, β-BaB_2O_4 (BBO) and LiB_3O_5 (LBO) have been well established as the nonlinear crystals [1,2]. Although these materials exhibit wide transmission ranges covering the UV wavelength region and high optical damage thresholds, their relatively low nonlinear optical coefficients (d_{eff} = 1~2 pm/V) needs to use a high-power IR laser as a fundamental wave source.

The newly developed monoclinic nonlinear crystal BiB_3O_6 (BiBO), which belongs to the same family as a BBO and LBO, is a good candidate for the frequency conversion of continuous-wave (CW) or low-power pulsed lasers. Although its UV transmission cutoff starts longer wavelength region than that of BBO and LBO, the BiBO possesses a rather high second-order nonlinear coefficient which exceeds that of BBO and LBO by about 1.7 and 4 times, respectively [3]. Furthermore, BiBO shows the high optical damage threshold as well as BBO and LBO, versatile phase-matching properties, and large angular and spectral acceptance bandwidth. These outstanding features make BiBO very attractive as a nonlinear medium for high-efficiency frequency conversions of not only high-power pulsed lasers but also low-power fundamental sources. In fact, a number of SHG experiments have been performed in BiBO, including single-pass SHG of pulsed Nd:YAG laser at 1064 nm [4], intracavity SHG of CW Nd:YAG laser at 946 nm [5], tunable single-pass SHG of picosecond and femtosecond Ti:sapphire laser [6,7], and single-frequency SHG of CW Ti:sapphire laser with a robust external enhancement ring cavity [8].

For the frequency conversion of CW or mode-locked lasers, an external enhancement cavity is the most important system to obtain high conversion efficiency because it is able to enhance the fundamental wave from laser source dramatically without any complex and expensive devices. Indeed, high-efficiency SHGs of CW and mode-locked picosecond Ti:sapphire laser have been reported through the external cavity in UV region [9,10]. Rather in this work, we demonstrated a high-efficiency SHG of a low-power mode-locked picosecond Ti:sapphire laser, whose average output power was less than 1 W, using a BiBO nonlinear crystal installed in an external enhancement cavity.

2. Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 1. The fundamental wave source was a mode-locked picosecond Ti:sapphire laser (Spectra-Physics Ins., Tsunami) pumped by a diode-pumped intracavity-frequency-doubled $Nd:YVO_4$ laser (Spectra-Physics Ins., Millennia Vs). The Ti:sapphire laser operating at 778 nm generated 1.1-ps pulse at 81.7-MHz repetition rate. The output of the Ti:sapphire laser, whose polarization was adjusted to s-polarization by a $\lambda/2$ plate (HWP) and a polarization beam splitter (PBS), was passed through a mode-matching lens (ML, f = 1000 mm) which was used to optimize the degree of mode-matching, and then introduced into an external enhancement cavity. The external cavity consisted of two planar mirrors (M1, M2) and two concave mirrors (M3, M4) with 250 mm radii of curvature. M1 was an input coupling mirror with a reflectance of 44%, whereas the other mirrors (M2-M4) were coated for high reflection at the fundamental wave (λ = 778 nm). The

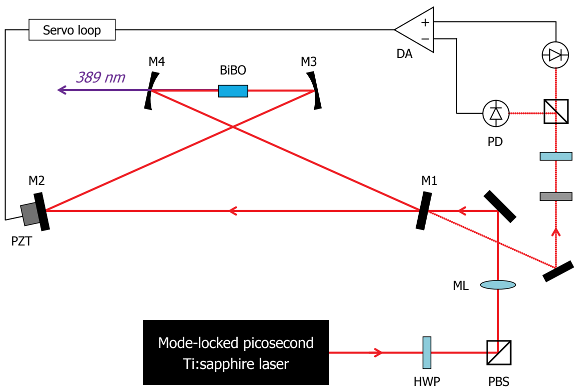

Fig. 1 Schematic experimental setup for SHG of a mode-locked picosecond Ti:sapphire laser with a BiBO. HWP, $\lambda/2$ plate; PBS, polarization beam splitter; ML, mode-matching lens; ND, neutral density filter; QWP, $\lambda/4$ plate; PD, photodetector; DA, differential amplifier; PZT, piezoelectric transducer.

reflectance of M1 was chosen in order to optimize the degree of optical impedance-matching. M4 was also coated dichromatically for high transmittance of 91% at the second harmonic wave (λ = 389 nm) as the output coupler. The cavity length of approximately 3669 mm was actively locked through the Hänsch-Couillaud (H-C) frequency stabilization scheme [11] so that the free spectral range of the external cavity was equal to that of the Ti:sapphire laser. The H-C scheme was performed by a $\lambda/4$ plate (QWP), a PBS, and a pair of photodetectors (PDs). The error signals were generated by a differential amplifier (DA) and fed back to the displacement of M2 mounted on a piezoelectric transducer (PZT) through servo loop.

A 3(W)×3(H)×15(L)-mm^3 BiBO crystal was placed between two concaved mirrors which focused circulating fundamental wave between them. The BiBO was cut for collinear critical type-I ($e + e \rightarrow o$) phase-matching direction (θ, φ) = (149.3°, 90°). Both end facets of the BiBO were applied antireflection coating at both fundamental and second harmonic waves. The beam radius of fundamental wave at the center of the BiBO was determined to be 35.4 μm in order to maximize the Boyd-Kleinman (B-K) focusing function [12]. According to the B-K theory, the second harmonic power $P_{2\omega}$ generated by a nonabsorbing nonlinear crystal is given by

$$P_{2\omega} = \eta P_{\omega}^2 = \frac{2\omega^2 d_{eff}^2 k_{\omega}}{\pi \varepsilon_0 n_1^2 n_2 c^3} L_c P_{\omega}^2 h(\sigma, B, \xi), \quad (1)$$

where P_ω, η, ω, d_{eff}, k_ω, ε_0, n_i (i = 1, 2), c, L_c, and $h(\sigma, B, \xi)$ are the fundamental power, the conversion efficiency [W^{-1}], the frequency of the fundamental wave, the effective nonlinear coefficient of the crystal, the wavenumber of the fundamental wave, the permittivity of vacuum, refractive indices of the crystal at the fundamental wave (i = 1) and second harmonic wave (i = 2), the speed of light in vacuum, the crystal length, and the B-K focusing function, respectively. The B-K function $h(\sigma, B, \xi)$ is defined as

$$h(\sigma, B, \xi) = \frac{1}{4\xi} \int_{-\xi}^{\xi} \int_{-\xi}^{\xi} \frac{e^{i\sigma(\tau-\tau')} \cdot e^{-B^2(\tau-\tau')^2/\xi}}{(1+i\tau)(1-i\tau)} d\tau d\tau', \quad (2)$$

where σ, B, and ξ are the normalized phase-mismatch, the nondimensional walk-off parameter, and the focusing parameter, respectively. In our experiment, the maximum of the B-K function $h(\sigma, B, \xi)$ was derived as 0.128 at $\sigma = 0$ (perfect phase-matching), B = 5.38, and ξ = 1.48. This calculation showed that the optimum beam radius of the fundamental wave was 35.4 μm at the center of the BiBO.

3. Results and discussion

Figure 2 shows the output second harmonic average power and the conversion efficiency as a function of input fundamental average power with the external enhancement cavity. The conversion efficiency was defined as the second harmonic average power divided by the input fundamental average power to the cavity. We obtained the maximum power of the second harmonic wave of 506 mW, corresponding to a conversion efficiency of 63%. Taking into account the reflective loss of 9% at the output coupler (M4), the generated second harmonic power in the cavity was estimated to be 560 mW, corresponding to the intrinsic conversion efficiency of 70%. This result, to the best of our knowledge, is the highest conversion efficiency for SHG using a BiBO, even at the relatively low fundamental power of 805 mW.

In order to evaluate our results theoretically, we used the equations described as [10]

$$P_{2\omega} = T_4 \gamma_{2\omega} P_c^2, \quad (3)$$

$$\frac{P_c}{P_\omega} = \frac{4T_1 m}{(T_1 + L + \gamma_{2\omega} P_c)^2}, \quad (4)$$

$$\frac{P_r}{P_\omega} = (1-T_1)(1-m) + \frac{(T_1 - L - \gamma_{2\omega} P_c)^2}{(T_1 + L + \gamma_{2\omega} P_c)^2} m, \quad (5)$$

where T_4, $\gamma_{2\omega}$, P_c, T_1, m, L, and P_r are the transmittance of the output coupler (M4) at the second harmonic wave, single-pass conversion efficiency [W^{-1}], the intracavity power of the fundamental wave, the transmittance of input coupler (M1) at the fundamental wave, mode-matching factor ($0 < m < 1$), the round-trip intracavity linear loss, and the reflected power of the fundamental wave, respectively.

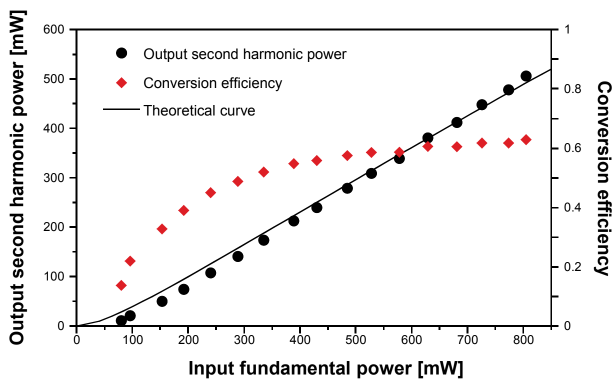

Fig. 2 Output second harmonic average power and conversion efficiency as a function of input fundamental average power with the external enhancement cavity. The black solid curve shows the best fit to the experimental data using the equation (3)-(5).

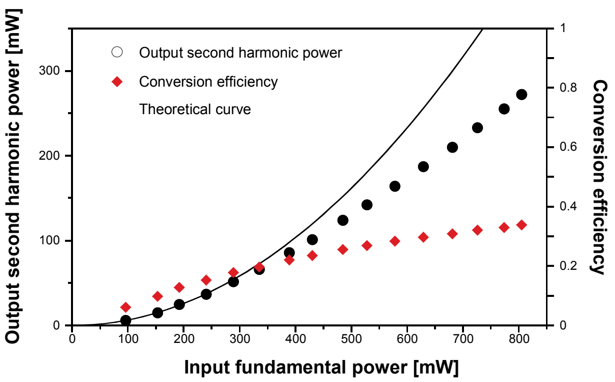

Fig. 3 Single-pass second harmonic average power and conversion efficiency as a function of input fundamental average power. The black solid curve is the best fit to the experimental data using the equation (6).

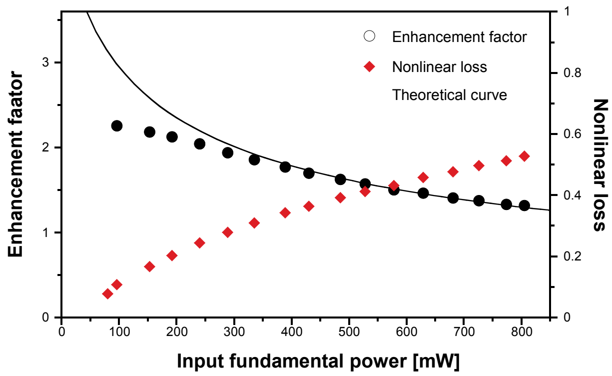

Fig. 4 Enhancement factor and intracavity nonlinear loss as a function of input fundamental power. The black solid curve is a calculated theoretical prediction of the enhancement factor.

We also performed the single-pass SHG experiment by removing the input coupler (M1) of the external cavity in order to obtain the single-pass conversion efficiency $\gamma_{2\omega}$. Figure 3 shows the single-pass output power of second harmonic wave and the conversion efficiency as a function of input fundamental power. The second harmonic power of 272 mW with a conversion efficiency of 34% was obtained and $\gamma_{2\omega}$ = 0.50 W^{-1} was estimated from a fitted equation

$$P_{2\omega} = T_4 \gamma_{2\omega} P_{\omega}^{\ 2}. \qquad (6)$$

As can be seen in Fig. 3, the deviation from the equation (6) means the significant depression of the fundamental wave in the crystal. Then, using the aforementioned equations (3)-(5), the intracavity linear loss and mode-matching factor was calculated to be L = 3.6% and m = 0.72, respectively. This relatively large linear intracavity loss L is mainly due to the imperfect coating of the cavity mirrors and the crystal and the absorption and/or scattering inside the BiBO crystal. Also, this relatively high mode-matching factor m presents the good alignment of the external cavity.

Enhancement factor of the fundamental wave in the external cavity is shown in Fig. 4. The enhancement factor ε is defined as

$$\varepsilon = \frac{P_c}{P_\omega}. \qquad (7)$$

We obtained the enhancement factor of about 1.4 when the intrinsic conversion efficiency was 70%. This factor decreases with increasing input fundamental power because the intracavity nonlinear loss of the conversion to second harmonic wave increases. The black solid curve in Fig. 4 is the theoretical prediction using the equations (3), (4), and (7). Figure 4 also shows the nonlinear loss as a function of input fundamental power. The nonlinear loss α_{nl} is given by

$$\alpha_{nl} = \gamma_{2\omega} P_c. \qquad (8)$$

When we obtained the maximum conversion efficiency of 70%, the nonlinear loss was 53%, corresponding to the total intracavity loss of about 57%. This relatively large loss was due to the high single-pass conversion efficiency ($\gamma_{2\omega}$ = 0.50 W^{-1}). Although the total loss was more than 50%, we achieved the fundamental power enhancement of 1.4, corresponding to the enhancement of second harmonic power of about 1.9.

For high-efficiency frequency conversion using the external cavity, the degree of optical impedance-matching is one of the most important factors. The impedance-matching could be achieved when the transmittance of the input coupler of the cavity equals to the total of all intracavity losses, including the power-dependent nonlinear losses, that is,

$$T_{1,opt} = L + \alpha_{nl} = L + \gamma_{2\omega} P_c, \qquad (9)$$

where $T_{1,opt}$ is the optimum transmittance of the input coupler at the fundamental wave. In this experiment, the total intracavity loss at the maximum second harmonic output and the transmittance of input coupler (M1) were ~57% and 56%, respectively. Therefore, we achieved the almost perfect impedance-matching.

4. Conclusion

We demonstrated a high-efficiency SHG of a low-power mode-locked picosecond Ti:sapphire laser using a BiBO nonlinear crystal. By using the external cavity, we achieved nearly twice higher conversion efficiency than the single-pass configuration. Considering the reflective loss at the output coupler, we obtained UV coherent light at 389 nm with the maximum average power of 560 mW through the external cavity, corresponding to the conversion efficiency of 70%. This result, to the best of our knowledge, is the highest conversion efficiency for SHG using a BiBO, even at the relatively low fundamental power. Our result obviously shows the superior performance of BiBO installed in the external cavity for SHG of low-power fundamental sources.

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