Spectral properties of second-harmonic generation at 800 nm in a BiB_3O_6 crystal

Tetsuo Harimoto

Faculty of Engineering, University of Yamanashi, 4-3-11 Takeda, Kofu, Yamanashi 400-8511, Japan
harimoto@yamanashi.ac.jp

Yasuki Takeuchi

Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka, Suita, Osaka 565-0871, Japan

Masayuki Fujita

Institute for Laser Technology, 2-6 Yamada-oka, Suita, Osaka 565-0871, Japan

Abstract: We have investigated spectral distribution and walk-off effect of second-harmonic generation in a 3-mm-long type I BiB_3O_6 crystal. Linearly turning ability of the BiB_3O_6 crystal is confirmed for wavelengths around 800 nm. In addition, the walk-off effect of fundamental beams is quantitatively measured by introducing a little vertical polarization component into pumping fundamental pulses. A conversion efficiency of 28% from fundamental to second harmonic is achieved at a 3.2-GW/cm^2 fundamental intensity.

OCIS codes: (190.2620) Frequency conversion; (190.7110) Ultrafast nonlinear optics

References and links

1. H. Hellwig, J. Liebertz, and L. Bohaty, "Linear optical properties of the monoclinic bismuth borate BiB_3O_6," J. Appl. Phys. **88**, 240-244 (2000).
2. C. Czeranowsky, E. Heumann, and G. Huber, "All-solid-state continuous-wave frequency-doubled Nd:YAG-BiBO laser with 2.8 W output power at 473nm," Opt. Lett. **28**, 432-434 (2003).
3. C. Du, Z. Wang, J. Liu, X. Xu, B. Teng, K. Fu, J. Wang, Y. Liu, and Z. Shao, "Efficient intracavity second-harmonic generation at 1.06 mm in a BiB_3O_6 (BIBO) crystal," Appl. Phys. B **73**, 215-217 (2001).
4. Z. Wang, B. Teng, K. Fu, X. Xu, R. Song, C. Du, H. Jiang, J. Wang, Y. Liu, Z. Shao, "Efficient second harmonic generation of pulsed laser radiation in BiB_3O_6 (BIBO) crystal with different phase matching directions," Opt. Commun. **202**, 217-220 (2002).
5. J. Yao, W. Sheng, and W. Shi, "Accurate calculation of the optimum phase-matching parameters in three-wave interactions with biaxial nonlinear-optical crystals," J. Opt. Soc. Am. B **9**, 891-902 (1992).

1. Introduction

BiB_3O_6 (BIBO) is a highly promising nonlinear optical crystal with a larger nonlinear optical coefficient and a high damage threshold. The BIBO crystal has a transmission range from 286 nm to 2500 nm, and is suitable for phase-matching condition for near infrared wavelengths [1]. Some research groups have investigated properties of second-harmonic generation (SHG) in the BIBO crystal. By introducing frequency doubling to a diode-pumped Nd:YAG laser with the BIBO crystal, a continuous-wave (CW) blue radiation at 473 nm up to 2.8 W is realized [2]. A CW output of 3.64 mW at 532 nm is obtained from an intracavity SHG in the type I BIBO crystal [3]. For an SHG with a 35-ps laser pulse at a 10-Hz repetition rate in the type I BIBO crystal, a conversion efficiency of 67% is achieved, which is much larger than that of $KTiOPO_4$ crystal [4]. However, SHG properties of the BIBO crystal for femtosecond

#3630 - $15.00 US Received 6 January 2004; revised 22 February 2004; accepted 23 February 2004

laser pulses have not been investigated to date. In this paper, we report our experimental results on spectral and walk-off properties of the SHG in the type I BIBO crystal with 100-fs laser pulses around 800 nm.

2. Experimental setup

Figure 1 is an experimental setup for the SHG in the BIBO crystal. A Ti:sapphire laser system is used as a pumping fundamental source, which has a central wavelength of 800 nm, a spectral bandwidth of 10.9 nm and a pulse duration of 100 fs. Low and high output powers can be provided at two repetition rates of 80 MHz and 1 kHz, respectively, so that experimental alignment can be easily carried out, and the spectral properties of the SHG in the BIBO crystal can be easily investigated. The polarization of the laser beam is primarily horizontal direction companying with a little vertical polarization component. A neutral density filter (ND) is inserted in order to adjust powers incident to the BIBO crystal. For 80-MHz fundamental laser pulses with lower powers, two convex lenses with focal lengths f_1=75 mm and f_2=25 mm are used to reduce the diameter of the incident laser beam, and increase the intensity of the fundamental beam subsequently. The lenses are finely adjusted to obtain Rayleigh range much larger than the thickness of the crystal. A 3-mm-long type I BIBO crystal (CRYSTECH Inc.), cut for the direction of $(\theta_m, \Phi)=(151°, 90°)$ with angular tolerances of $(\Delta\theta_m, \Delta\Phi)<(0.3°, 0.3°)$, is AR coated at 800 nm and 400 nm on both faces. The flatness of the crystal is $\lambda/8$ at 633 nm. The parallelism and perpendicularity are better than 20 arc seconds and 5 arc minutes, respectively. The acceptance bandwidth is calculated to be 7.8 cm^{-1} for one cm long crystal at 800 nm. The crystal is placed on a stage, which is possible for turning at both vertical and horizontal directions, and rotating at a minimum step of 1 arc minute with an accuracy of better than 1%. A filter placed in front of a power meter (Spectral Physics model 407A) is used to cutoff the residual fundamental portion transmitted through the crystal. Spectral distributions of fundamental and second-harmonic (SH) pulses are measured with a photonic multi-channel analyzer (Hamamatsu Photonics PMA-11) with a spectral resolution of 0.75 nm, and spatial profiles are monitored with a laser beam analyzer (Spirincon model LBA-100A).

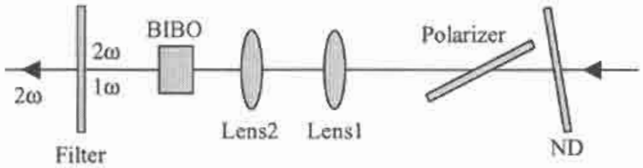

Fig. 1. Experimental schematic for SHG in a type I BIBO crystal. 1ω and 2ω denote fundamental and SH pulses, respectively.

3. Experimental results and discussion

Figure 2 shows the spectral properties of the SHG as functions of the externally turning angle $\Delta\theta_e$ with the 100-fs laser pulse at the 80-MHz repletion rate. The average power of incident fundamental pulses is 390 mW, and the corresponding power per pulse is 48.8 kW. The central wavelength of the fundamental pulse with Gaussian distribution is 799 nm. The horizontal axis of Figs. 2(a), 2(b), and 2(c) is the external angle $\Delta\theta_e$ incident on the crystal, and the corresponding internal angle $\Delta\theta_i$ is approximately expressed by $\Delta\theta_e=\Delta\theta_i/n_1$, where n_1 is the index of the crystal for the fundamental laser pulse. For a monochromatic fundamental wave, the turning angle corresponds to the phase-mismatching angle at the given fundamental wavelength. For a broadband laser pulse, however, the turning angle means the variation in the phase-matching angle, and the central fundamental wavelength is subsequently turned with respect to the phase-matching angle. The SH profile shown in Fig. 2(a) is almost the reproduction result of the fundamental spectral profile. As shown in Fig. 2(b), the central wavelength of the SH pulse varies linearly with the turning angle $\Delta\theta_e$, and the wavelength

#3630 - $15.00 US Received 6 January 2004; revised 22 February 2004; accepted 23 February 2004

variation $\Delta\lambda_2$ of the SH pulse can be approximately expressed by $\Delta\lambda_2$=3.0$\Delta\theta_e$. With the Sellmeier equation of the BIBO crystal, $\Delta\lambda_2$ can be theoretically expressed by $\Delta\lambda_2$=2.74$\Delta\theta_e$ around 400 nm, which is approximately in accordance with the experimental result. We can see some steps in Fig. 2(b) due to the resolution limitation of the photonic multi-channel analyzer. Spectral bandwidths of the SH pulse at full-width half-maximum (FWHM) shown in Fig. 2(c) for relatively long wavelengths or larger phase-matching angles are slightly broader than those for short wavelengths, which are also in accordance with the numerical result for the acceptable bandwidth of the SH pulse. In comparison with the bandwidth of the fundamental pulse, the SH bandwidth is reduced by a factor of 5 due to the limitation of the acceptable bandwidth of the BIBO crystal for the 3-mm-long crystal. The corresponding spectral shapes of the fundamental and SH pulses are shown in Fig. 2(d).

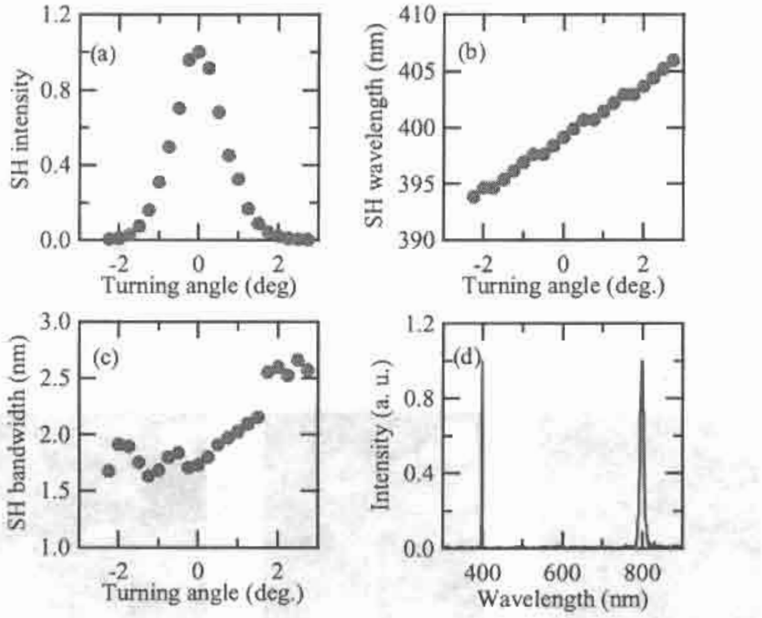

Fig. 2. Spectral properties of SHG in a 3-mm-long type I BIBO crystal. (a) SH intensity; (b) SH wavelength; (c) SH bandwidth; (d) Spectral distributions of fundamental (1ω) and SH (2ω) pulses.

Figure 3 is the dependence of the normalized power and the bandwidth of the SH pulse on the fundamental peak power at the central wavelength of 799 nm. The SH power increases linearly with the fundamental peak power if the fundamental peak power is over 25 kW. In addition, the SH bandwidth also increases with the fundamental power because the intense laser power easily induces the SH conversion process for a relative broadband spectral range.

Figure 4 shows spatial patterns of the fundamental beam incident to the crystal, residual fundamental beam transmitted through the crystal, and generated SH beam under the same conditions used in Fig. 3. In order to observe the walk-off effect in the BIBO crystal, we introduce a little component of the vertical polarization into the fundamental pulse which has primarily horizontal polarization direction. The horizontal polarization component of the fundamental laser pulse satisfies the requirement of the phase-matching condition for the type I BIBO crystal. At the same time, the vertical polarization component will transmit through the crystal except for a little absorption in the crystal, resulting in the left peak (denoted as peak 1) in Fig. 4(b). The vertical polarization portion without any direction shift due to the walk-off effect is used as a propagation-direction reference of the input fundamental beam. In

#3630 - $15.00 US Received 6 January 2004; revised 22 February 2004; accepted 23 February 2004

addition, the fundamental beam polarized at the horizontal direction is an extraordinary component, which will propagate within the crystal at the walk-off angle in comparison with the vertical component, resulting in a spatial shift (denoted as peak 2) in the propagation direction in comparison with its incident direction to the crystal. Based on Yao's calculation formulation [5], the walk-off angle for the type I BIBO crystal is 59 mrad at 800 nm, therefore the spatial shift at the output face of the 3 mm-long crystal is approximately 0.18 mm, which agrees with the experimental result shown in Fig. 4(b). The spatial pattern of the SH beam is shaped by the SHG process, and is slightly distorted in comparison with that of the input fundamental beam due to the walk-off effect along the X direction [Fig. 4 (c)].

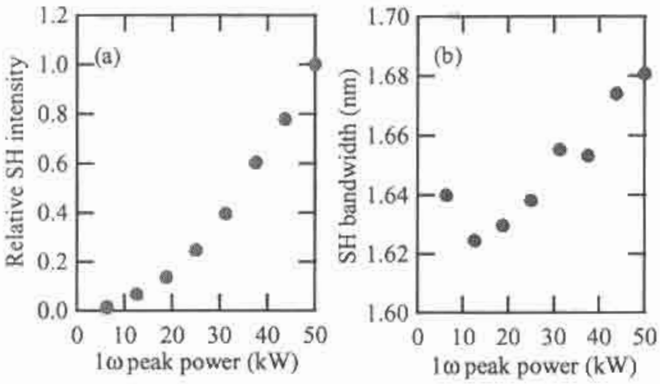

Fig. 3. Dependence of (a) SH intensity and (b) bandwidth on the fundamental peak intensity incident to the BIBO crystal.

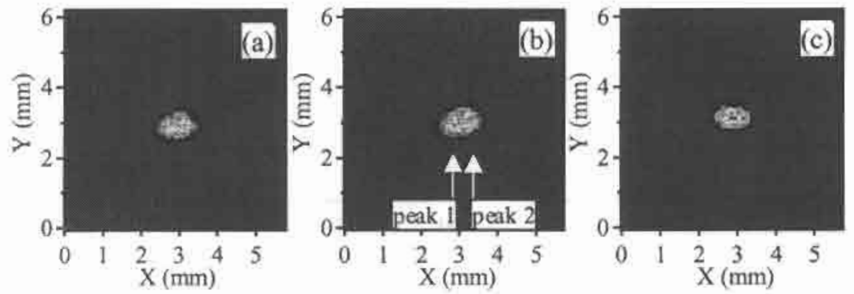

Fig. 4. Spatial patterns of (a) input fundamental, (b) residual fundamental, and (c) SH beams. X and Y denote the x- and y-direction axes of the patterns, respectively.

The conversion efficiency of the SHG in the BIBO crystal is further measured by using 100-fs high power Ti:sapphire laser pulses at a 1-kHz repetition rate. The convex lenses f_1 and f_2 shown in Fig. 1 are removed from the experimental scheme in order to avoid any possible breakdown of the fundamental pulses between f_1 and f_2 due to the high laser powers. The breakdown problem can be generally avoided by replacing the convex lens f_1 with a concave lens. The conversion efficiency, defined as the average power ratio of SH to fundamental pulses, is shown in Fig. 5 at different peak powers of the fundamental pulses. The maximum conversion efficiency of as high as 28 % is obtained at the fundamental average power of 10 mW, which corresponds to 0.1 GW per pulse or 3.2 GW/cm^2 for a beam diameter of 2 mm. Due to the limitation of the power meter we used, conversion efficiency data for fundamental peak powers lower than 0.05 GW could not be obtained in our experiment. For peak incident powers from 0.05 GW to 1 GW, SH conversion efficiencies are over 20% entirely. The average value of power fluctuations of SH laser pulses, which are primarily resulted from power fluctuations of fundamental laser pulses, is 5.7% for input fundamental powers of 0.05

#3630 - $15.00 US
Received 6 January 2004; revised 22 February 2004; accepted 23 February 2004

~1 GW. We find no thermal effect affecting the SHG performance for 80-MHz fundamental pulses with lower input powers. However, the conversion efficiency for the central portion of the SH pattern is slightly decreased due to the thermal effect within the crystal when 1-kHz high-power fundamental pulses irradiate the crystal continuously over ten minutes. In addition, there is no any damage on the crystal at the given powers.

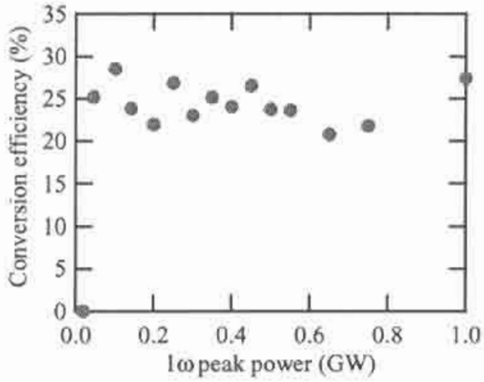

Fig. 5. Conversion efficiency of SH pulse as a function of the input fundamental peak intensity.

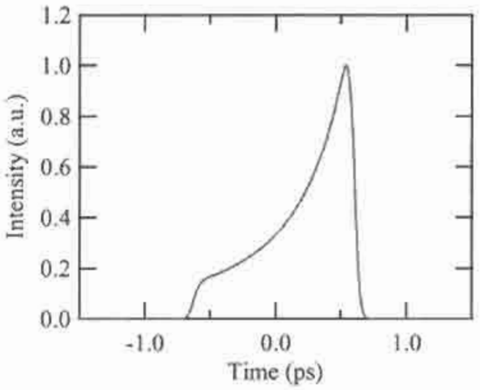

Fig. 6. Calculated temporal profile of the SH pulse under the experimental conditions.

In order to investigate the spectral and walk-off properties of the SHG in the BIBO crystal, we used a 3-mm-long crystal in the experiment. For a 100-fs laser pulse, group-velocity mismatch (GVM) should be considered in the optimum design of the BIBO crystal. The GVM effect limits the suitable crystal thickness to $\tau_1/(1/v_1-1/v_2)$ in order to avoid the SH pulse stretch, where τ_1 is the duration of the fundamental pulse, v_1 and v_2 are the group-velocities of the fundamental and SH pulses, respectively. This corresponds to a crystal thickness that must be less than 0.24 mm for the 800-nm fundamental wavelength, which is shorter than that used in the experiment. Therefore, the SH pulse duration obtained in the experiment will be longer than that of the incident fundamental pulse. We carried out numerical estimation for the SH pulse profile with nonlinear wave equations involving the GVM effect. Figure 6 is the calculated temporal profile of the SH pulse under the experimental conditions. The SH duration (FWHM) is estimated to be 370 fs and the SH profile is not Gaussian anymore due to the GVM effect. The pulse stretch and distortion can be avoided by using a 0.24-mm-long BIBO crystal and higher conversion efficiencies could be expected by using higher fundamental intensities.

#3630 - $15.00 US Received 6 January 2004; revised 22 February 2004; accepted 23 February 2004

4. Conclusions

We have experimentally investigated spectral and walk-off properties of SHG in a type I BIBO crystal. Linear wavelength-turning ability of the BIBO crystal around 800 nm is confirmed. By introducing a little component of the vertical polarization into the fundamental pulse, the walk-off effect is quantitatively measured. The SH conversion efficiency of as high as 28 % is achieved at the fundamental intensity of 3.2 GW/cm^2.