Efficient Frequency Doubling of a Low-Power Femtosecond Er-Fiber Laser in BiB_3O_6

Kentaro Miyata, Fabian Rotermund, and Valentin Petrov

***Abstract*—BiB_3O_6 (BIBO) crystal has been used for efficient second-harmonic generation (SHG) of a low-power femtosecond Er-fiber laser-amplifier system operating at 56 MHz. At the maximum input power of 65 mW, an internal conversion efficiency of 23% was achieved for SHG at 782 nm, with a pulse duration of 64 fs. A comparison with β-BaB_2O_4 reveals superior properties of BIBO for such ultrashort-pulse ultra-broadband SHG.**

***Index Terms*—Bismuth triborate, Er-fiber laser, second-harmonic generation (SHG).**

I. Introduction

MODE-LOCKED Er-fiber lasers are compact and stable ultrashort light pulse sources operating at high repetition rate near 1600 nm. Their frequency doubling to $\sim$ 800 nm is useful for injection seeding of femtosecond (fs) regenerative amplifiers, and can be a promising alternative to existing fs Ti : Sapphire lasers. In fact, due to the broad tunability of existing optical parametric generator/amplifier (OPG/OPA) systems pumped by fs Ti : Sapphire amplifiers, there is a trend to simplify such pump sources by fixing their wavelengths near 800 nm by using the second harmonic (SH) of Er-fiber lasers as a seed. The first such attempt of frequency doubling a fs Er-fiber laser aimed at injection seeding an alexandrite regenerative amplifier, and SH pulses at 796.3 nm having pulse duration of 61 fs and energy of 30 pJ were obtained from the 1.5-nJ fundamental pulses [1]. Output power of Er-fiber lasers, however, is rather low in this sub-100 fs regime, even with the addition of Er-fiber amplifiers, and this makes the SH generation (SHG) inefficient. Thus, using a 1-cm-long β-BaB_2O_4 (BBO) crystal, a conversion efficiency of 5% for 73-fs-long SH pulses at 772 nm was obtained [2]. Subsequently, higher input energy of 2.7 nJ resulted in 10% efficiency, 86-fs SHG [3]. At a repetition rate of 31.8 MHz, these results correspond to SH energies of 91 and 270 pJ, respectively. Introducing the quasi-phase-matching (QPM) technique, higher conversion efficiency of 25% was achieved with a 1-mm-long, periodically poled $LiNbO_3$ (PPLN) crystal [4], generating 90-pJ, 190-fs pulses at 777 nm. Finally, using much higher power, 230 mW, of Raman-shifted pulses from an Er-Yb-fiber master–oscillator/power-amplifier system, a 105-fs SHG at 810 nm with an average power of 117 mW was demonstrated with a 0.6-mm-long PPLN crystal [5]. The measured energy was as high as 2.3 nJ at 52 MHz and the conversion efficiency reported was 51%. However, with the significant improvement of the output power/energy and conversion efficiency, the pulse duration at the SH tends to become considerably longer than that reported in the first demonstration of 61-fs SH pulses [1], and the SH pulses, in general, become not bandwidth limited.

To preserve the short-pulse duration of the fundamental, broad spectral acceptance bandwidth is required. The type-0 (ee-e) PPLN crystal possesses a very narrow bandwidth of $\Delta\lambda\ell \sim 1$ nm $\cdot$ cm [full-width at half-maximum (FWHM)]. Therefore, the crystal length needs to be extremely short, which, despite the large effective nonlinear constant ($d_{\text{eff}} = 16.5$ pm/V [2]), requires tight focusing in the SHG crystal to achieve high conversion efficiency (e.g., $w_o = 10\ \mu$m for $\ell = 1$ mm [2]). This indicates the limits of this material for an ultimately short pulse ($\tau < 100$ fs), having in mind the damage threshold also. In contrast, the spectral bandwidth of type-1 BBO [6] is extremely large, as will be shown later, but the small angular acceptance ($\Delta\theta_{\text{ext}}\ell \sim 1.4$ mrad $\cdot$ cm) and large walk-off angle ($\rho \sim 2.8^\circ$) have limited the achievable conversion efficiency, and led to spatially poor beam quality [1].

To overcome these problems, type-1 QPM for 5-mol%-MgO-doped PPLN [7], [8] and periodically poled $KNbO_3$ (PPKN) crystals [9] were proposed. Due to the zero group-velocity mismatch (GVM), the spectral bandwidths for these materials become substantially larger compared to the type-0 process. The measured spectral bandwidths at the corresponding zero-GVM points were $\Delta\lambda \sim 52$ nm at 1566 nm for a 1-cm MgO : PPLN and $\Delta\lambda \sim 38$ nm at 1518 nm for a 1-cm PPKN. These modest bandwidths are attributed to the large group-velocity dispersion (GVD) at the SH caused by the low energy bandgaps of these niobate crystals. In addition, pulse broadening of the SH has been observed at the zero-GVM points for both materials using the 95-fs-long fundamental pulses from OPA and explained by the large GVD at the SH. Nevertheless, although these materials are extremely sensitive to the temperature, the processes are angularly noncritical, and when compared to BBO, the effective nonlinearities are $\sim$ 1.3 and $\sim$ 3.3 times larger for MgO : PPLN and PPKN, respectively. Similarly, type-2 QPM has been proposed for periodically poled $KTiOPO_4$ crystal [10]. This material possesses comparable effective nonlinearity

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to that of BBO, and slightly larger spectral acceptance than the aforementioned periodically poled crystals at the zero-GVM point ($\Delta\lambda \sim 67$ nm for 1-cm-length at 1584 nm), but the two different group velocities of fundamental present additional limitations in the case of fs-pulse interactions. Unfortunately, no experimental demonstration of fs SHG has been reported in this letter.

Taking into account the properties of existing nonlinear crystals as well as the quality and size available, type-1 BBO still seems to be one of the best candidates for sub-100 fs pulses. Here, we report experimental demonstration of fs-pulse SHG of an Er-fiber laser-amplifier system at 1564 nm with the monoclinic nonlinear crystal BiB_3O_6 (BIBO), which is readily available with high quality and large size. Rigorous comparison with BBO confirmed that BIBO possesses superior properties for such SHG. Keeping the fundamental pulse duration unchanged, transform-limited 64-fs SH pulses with conversion efficiency as high as 23% have been obtained by using a 5-mm-long BIBO crystal. Also, a maximum conversion efficiency of 27% with a slightly longer SH pulse duration of 73 fs has been obtained with a 6-mm-long sample of BIBO.

II. Spectral Acceptance of BIBO and BBO for SHG

Recently, Ti : Sapphire regenerative amplifier pumped, ultrabroadband degenerate OPA has been demonstrated with BIBO [11], which was mainly attributed to the large effective nonlinearity and the unique group-velocity parameters of this crystal for the type-1 (oo-e) interaction in the x-z plane. Since type-1 SHG is the reverse process, this material should be interesting for frequency doubling of fs Er-fiber lasers also.

For SHG of short pulses, large spectral acceptance is always desirable, and this makes type-1 phase matching always preferable. The analytical analysis is simplified in this case by the fact that there is only one (inverse) GVM parameter, $\Delta_{13} = \Delta_{23} = 1/v_1 - 1/v_3$, in the three-wave interaction, where $v_1 = v_2$, and $v_{1,2}$ and v_3 are the group velocities of the fundamental and SH waves, respectively. This parameter is directly related to the spectral acceptance (FWHM) $\Delta\nu_1 = 0.443/(\ell|\Delta_{13}|)$, where ν_1 is the fundamental frequency and ℓ is the crystal length. This equation is strictly valid in the fixed-field approximation, equivalent to low conversion efficiency, but is also useful for the high conversion efficiency analysis. Only in the vicinity of the zero-GVM wavelength, it is necessary to consider the next order term in the expansion of the wave-vector mismatch, which leads to $\Delta\nu_1 = (0.886/\pi\ell|k_1'' - 2k_3''|)^{1/2}$, where k'' denotes the GVD of each of the interacting waves.

Note that GVD at the SH predominates for the second-order bandwidth. Fig. 1 shows the group-velocity parameters calculated for type-1 BIBO, with the Sellmeier equations from [12], and BBO, with the Sellmeier equations from [6], where the results for BIBO are presented only for the phase-matching branch useful for this application. It is clear that both crystals have very broad and similar spectral acceptance near 1600 nm, where mode-locked Er-fiber lasers operate. Since the zero-GVM condition is fulfilled simultaneously with the phase-matching condition at $\lambda_1 \sim 1637$ and ~ 1541 nm for BIBO and BBO, respectively, the GVD starts to play a role in the broadening of SH pulses at shorter operating wavelength for BBO and longer wavelength for BIBO. For instance, the spectral bandwidths for BIBO and BBO crystals are calculated to be $\Delta\lambda_1 \cdot \ell = 16$ nm $\cdot$ cm and $\Delta\lambda_1 \ell^{1/2} = 102$ nm $\cdot$ cm$^{1/2}$ at 1530 nm, respectively, and $\Delta\lambda_1 \ell^{1/2} = 89$ nm $\cdot$ cm$^{1/2}$ and $\Delta\lambda_1 \cdot \ell = 39$ nm $\cdot$ cm at 1620 nm (Raman-shifted wavelength), respectively. It should be noted that the large spectral acceptance of these crystals compared to the aforementioned MgO : PPLN [7], [8], PPKN [9], and PPKTP [10] crystals in the vicinity of their zero-GVM points is due to the relatively low GVD at the SH, see Fig. 1.

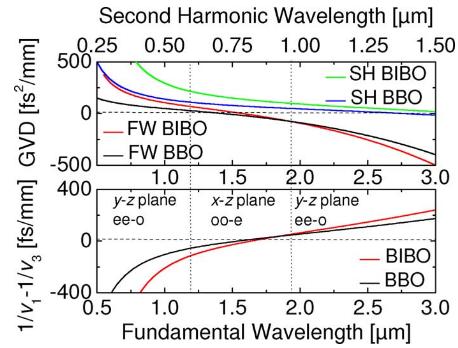

Fig. 1. (Bottom) Inverse GVM $(1/v_1 - 1/v_3)$ and (top) GVD (k'') for type-1 SHG in BIBO and BBO. FW: fundamental and SH: second harmonic.

In this letter, a fundamental source at 1564 nm with a pulse duration of ~ 60 fs has been used for frequency doubling. The spectral acceptance bandwidths are $\Delta\lambda_1 \ell = 25$ nm $\cdot$ cm and $\Delta\lambda_1 \ell^{1/2} = 107$ nm $\cdot$ cm$^{1/2}$ for BIBO and BBO, respectively, indicating a better performance with BBO in terms of spectral acceptance. However, it can be expected that BIBO can perform better even at this operating wavelength because this material exhibits much larger angular acceptance ($\Delta\theta_{\mathrm{ext}}\ell = 2.28$ mrad $\cdot$ cm), smaller walk-off angle ($\rho = 1.75°$), and ~ 1.5 times larger effective nonlinear constant ($d_{\mathrm{eff}} = 3.1$ pm/V). Given the spectral bandwidth of a transform-limited sech^2-shaped pulse, optimum crystal lengths to preserve pulse duration of our laser system are estimated to be between 5 and 6 mm.

III. Experiments and Discussion

Taking into account the spectral acceptance discussed before, 5- and 6-mm-long uncoated BIBO crystals were used, both cut at $\theta = 11.4°$ in the x-z plane, close to the exact phase-matching angle of $\theta_{\mathrm{pm}} = 10.9°$. The fundamental source was a diode-pumped, mode-locked (by nonlinear polarization rotation) Er-fiber laser-amplifier system at 56 MHz, generating a linearly polarized, diffraction-limited ($M^2 \cong 1.0$) beam with an average power of 65 mW and an energy of 1.16 nJ at 1564 nm. Intensity autocorrelation measurement with a 2-mm BBO crystal gave pulse duration of 59 fs, assuming a sech^2-shaped pulse. Several different lenses were tested for focusing the output beam into the SHG crystals and $f = 75$ mm was chosen to achieve maximum SH powers, where the beam spot radius at the focus was measured to be $w_o(1/e^2) \cong 25$ μm. A potassium dihydrogen phosphate (KDP) crystal was placed after the SHG crystals to block the fundamental beam in the

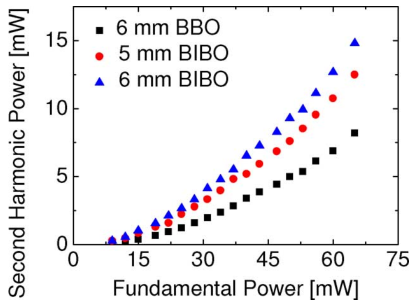

Fig. 2. Average SH power versus fundamental power.

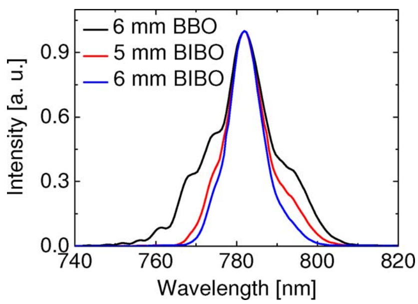

Fig. 3. Spectra of the SH pulses at 782 nm.

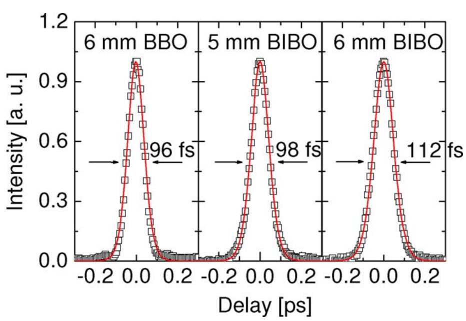

Fig. 4. Intensity autocorrelation (symbols) and fits (curves) for SHG at 782 nm.

power measurements, but this filter was removed during the spectral and autocorrelation measurements.

Fig. 2 shows the average power dependence between fundamental and SH beams measured with the 5- and 6-mm BIBO samples. At the maximum incident power of 65 mW, SH powers of 12.5 and 14.8 mW were observed with the 5- and 6-mm samples that correspond to internal conversion efficiencies as high as 23% and 27%, respectively. These results were compared with that of a 6-mm-long, uncoated type-1 BBO crystal, cut at $\theta = 19.9°$, under identical conditions (Fig. 2). The measured output power was approximately factor of 2.0–1.5 and 2.3–1.8 higher with the 5- and 6-mm BIBO, respectively, from the low to high input power levels. Note that the large conversion efficiency for BIBO at the high input power level has caused some saturation in SH powers, indicating fundamental power depletion. The maximum pulse energy achieved at the SH was 265 pJ.

The results of the spectral and temporal characterization are shown in Figs. 3 and 4, respectively. The irregular spectrum with BBO replicates the structure of the fundamental spectrum. A pulse duration of 62 fs is obtained in this case from the autocorrelation results, assuming a $sech^2$-shaped pulse, which leads, with the spectral FWHM of 15 nm, to a time-bandwidth product of $\tau\Delta\nu = 0.44$. In contrast, smooth SH spectra have been observed with the two BIBO samples, but with narrower bandwidths. The almost same pulse duration of 64 fs obtained with the 5-mm BIBO denotes a higher quality SH pulse ($\tau\Delta\nu = 0.35$), while the longer pulse duration of 73 fs for the 6-mm sample indicates that the slightly smaller acceptance bandwidth elongated the pulse. Nevertheless, the SH pulses were also bandwidth limited with the 6-mm BIBO, $\tau\Delta\nu = 0.34$.

IV. Conclusion

We demonstrated highly efficient frequency doubling of a low-power fs Er-fiber laser-amplifier system by using BIBO, and compared its performance with that of BBO. The present results, which evidence the higher conversion efficiency with BIBO at the same pulse duration of the SH, are clear indication of the superiority of this material over BBO for this application.

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