Efficient frequency doubling of a femtosecond Er-fiber laser using BiB_3O_6

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Abstract: BiB_3O_6 has been used for second-harmonic generation of a femtosecond Er-fiber laser-amplifier at 56 MHz. An internal conversion efficiency of 23% was obtained for second-harmonic pulses with a duration of 64 fs at 782 nm.

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Mode-locked Er-fiber lasers provide compact and stable ultrashort light sources near 1600 nm at high repetition rate. Frequency doubling to ~800 nm is useful for injection seeding of Ti:sapphire or alexandrite regenerative amplifiers [1]. Output power of Er-fiber lasers, however, is rather low in the sub-100-fs regime, even amplified in an Er-fiber amplifier, and this makes the second-harmonic generation (SHG) inefficient. Thus, using a 1-cm-long β-BaB_2O_4 (BBO) crystal, a conversion efficiency of 10% was achieved for 86-fs pulses at the second harmonic [2], corresponding to an energy of 270 pJ at 772 nm for a repetition rate of 31.8 MHz. Higher conversion efficiency of 25% was achieved with a 1-mm-long, periodically poled $LiNbO_3$ (PPLN) crystal [3], generating 90-pJ, 190-fs pulses at 777 nm.

To preserve the short pulse duration of the fundamental, broad spectral acceptance bandwidth of nonlinear crystal is required. The type-0 (ee-e) PPLN crystal possesses a very narrow bandwidth of $\Delta\lambda\cdot\ell \sim 1$ nm·cm (FWHM). Therefore, the interaction length needs to be extremely short despite the large effective nonlinear constant (d_{eff} = 16.5 pm/V [3]), which requires tight focusing inside the SHG crystal to achieve high conversion efficiency (e.g. w_o = 10 μm for ℓ = 1 mm [3]). This indicates the limits of this material for an ultimate short pulse (τ < 100 fs), having in mind also the damage-threshold. In contrast, the spectral bandwidth of type-1 BBO is very large, but the small angular acceptance ($\Delta\theta_{ext}\cdot\ell \sim 1.4$ mrad·cm) and large walk-off angle ($\rho \sim 2.8°$) limit the achievable conversion efficiency and lead to spatially poor beam quality [2]. Here we report efficient SHG of a low-power femtosecond Er-fiber laser-amplifier at 1564 nm by the use of a BiB_3O_6 (BIBO) frequency-doubler. Transform-limited 64-fs SHG pulses with an internal conversion efficiency as high as η = 23% have been obtained with a 5-mm-long sample. Also, a maximum conversion efficiency of η = 27% with a slightly longer SHG pulse of τ = 73 fs has been obtained with a 6-mm-long sample. An experimental comparison with a 6-mm BBO crystal is presented in detail.

BIBO is a positive biaxial crystal belonging to the monoclinic system with point symmetry 2. Since this material simultaneously fulfills the phase- and group-velocity matching (GVM) between fundamental and second-harmonic beams at $\lambda \sim 1.637$ nm [4], the spectral acceptance bandwidth for phase-matched SHG of an Er-fiber laser is expected to be large. The recently published Sellmeier equations [4] predict $\Delta\lambda\cdot\ell$ = 24.9 nm·cm at λ = 1564 nm in the *x-z* plane (θ_{pm} = 10.9°) for oo-e type-1 interaction, which is much broader than those of other existing nonlinear crystals, except BBO ($\Delta\lambda\cdot\ell$ > 100 nm·cm [5]). The very broad bandwidth of BBO is attributed to the fact that its phase-matching condition for GVM is located at $\lambda \sim 1547$ nm. However, BIBO exhibits larger angular acceptance ($\Delta\theta_{ext}\cdot\ell$ = 2.28 mrad·cm), smaller walk-off angle (ρ = 1.75°), and ~1.5 times larger effective nonlinear constant (d_{eff} = 3.1 pm/V). Given the spectral bandwidth of a transform-limited ~60-fs-long $sech^2$-shaped pulse, the crystal length to preserve the pulse-duration of our system is between 5 and 6 mm. Therefore, we compared two BIBO crystals, 5- and 6-mm-long, cut at θ= 11.4° in the *x-z* plane, with a 6-mm-long type-1 BBO crystal. All samples were uncoated.

The SHG experiments were carried out on a diode-pumped, mode-locked (by nonlinear polarization rotation) Er-fiber laser-amplifier. This system provided a linearly polarized, diffraction-limited ($M^2 \cong 1.0$) beam with an average power of 65 mW at a repetition rate of 56 MHz, corresponding to an energy of 1.16 nJ at 1564 nm. Intensity autocorrelation measurement with a 2-mm BBO crystal gave a fundamental pulse duration of 59 fs assuming a $sech^2$-pulse shape. Several different lenses were tested for focusing the output beam into the SHG crystals and f = 75 mm was chosen to achieve maximum SHG powers. The beam spot radius at the focus was measured to be w_o $(1/e^2) \cong 25$ μm. A KDP crystal was placed after the SHG crystals to block the fundamental beam in the power measurements but this filter was removed during the spectral and autocorrelation measurements.

Figure 1 shows the average power dependence between fundamental and second-harmonic beams measured with the 5- and 6-mm BIBO samples under the optimized focusing condition. At the maximum incident power of 65 mW, SHG powers of 12.5 and 14.8 mW were observed with the 5- and 6-mm samples which correspond to internal conversion efficiencies as high as 23% and 27%, respectively. These results were compared with that of the 6-mm BBO under identical condition (Fig. 1). 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 SHG powers, indicating fundamental power depletion. The maximum pulse energy achieved at the second harmonic was 265 pJ.

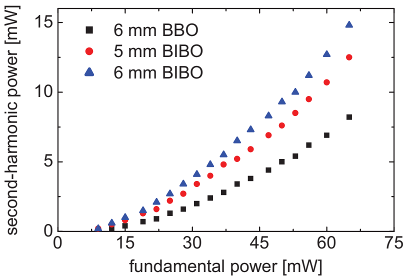

Fig. 1. Average second-harmonic power versus fundamental power.

The results of the spectral and temporal characterization are shown in Figs. 2 (a) and (b), respectively. The irregular spectrum with BBO replicates the structure of 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 second-harmonic 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 second-harmonic 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 second-harmonic pulses were bandwidth-limited also with this BIBO sample, $\tau\Delta\nu$ = 0.34. The present results, which evidence the higher conversion efficiency of BIBO at the same pulse duration of the second harmonic, are a clear indication of the superiority of this material over BBO for this application.

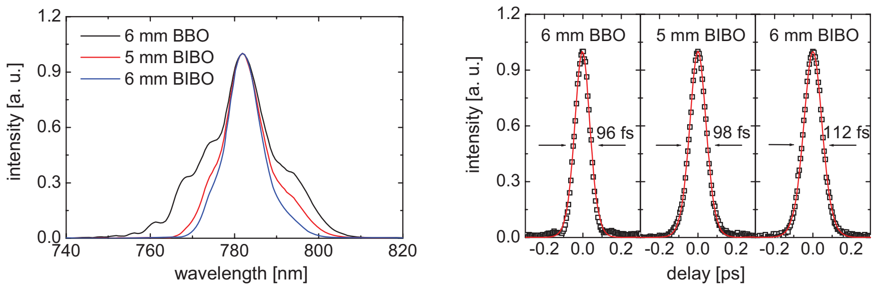

Fig. 2. Spectra of the second-harmonic pulses at 782 nm (a) and intensity autocorrelation traces (b).

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