Femtosecond nonlinear frequency conversion using BiB_3O_6 crystals from 250 nm in the UV to 3000 nm in the near-IR

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Abstract: Relevant properties of BIBO are reviewed and experimental results are presented on both parametric up- and down-conversion of femtosecond pulses, from the high-energy, low-repetition-rate (1-kHz) to the low-energy, high-repetition-rate (56-76-MHz) regime, demonstrating its unique versatility.

OCIS codes: (190.4400) Nonlinear optics, materials; (190.7110) Ultrafast nonlinear optics

I review the physical properties, linear and nonlinear optical characteristics, and phase-matching configurations of BiB_3O_6 (BIBO), the first low symmetry (monoclinic) inorganic nonlinear crystal that has found broad applications for frequency conversion of laser sources from the UV, across the visible, to the near-IR based on three-wave interactions. The most relevant optical properties that make this material an attractive candidate for nonlinear frequency conversion of laser light in general, and ultrafast femtosecond laser sources in particular, will be described. Several review papers (mostly conference papers) have appeared in the past but they covered all kinds of times scales [1-4] while the present discussion will focus on application of BIBO in the femtosecond time domain. These experiments have been realized, without exception, at ICFO - Institut de Ciencies Fotoniques (Barcelona, Spain) in the group of M. Ebrahim-Zadeh and at the Max-Born-Institute, MBI (Berlin, Germany).

With special focus on ultrafast frequency conversion, characteristics such as group velocity mismatch and spectral acceptance, parametric gain bandwidth, group velocity dispersion, as well as angular acceptance and spatial walk-off are evaluated and optimum configurations for the attainment of maximum conversion efficiency, minimum pulse duration, and highest spatial beam quality are identified and compared with the most widely established alternative borate crystal, β-BaB_2O_4. Experimental results are presented on both parametric up- and down-conversion of femtosecond pulses, from the high-energy, low-repetition-rate (1 kHz) to the low-energy, high-repetition-rate (56-76 MHz) regime, demonstrating the unique versatility of BIBO for efficient frequency conversion of femtosecond pulses with broad tunability from 250 nm in the UV, throughout the visible, up to ~3000 nm in the IR.

The generation of high repetition rate femtosecond pulses with wide tunability across the 375-435 nm in the blue spectral range at average power up to 830 mW with conversion efficiency in excess of 50% using simple single-pass SHG in BIBO of a mode-locked Ti:sapphire laser at 76 MHz, has been demonstrated. Conversion efficiency of 23% has been achieved for SHG at 782 nm of a low power (65 mW average power at the fundamental) femtosecond Er-fiber laser/amplifier operating at 56 MHz, preserving the pulse duration of ~60 fs. In intracavity SHG of a near-IR PPLN SPOPO average powers as much as 260 mW for 1.51 W of Ti:sapphire pump at 17.2% efficiency with a tunability range of the second harmonic across 665-785 nm in the red spectral range, have been achieved. Moreover, convenient wavelength tuning across the full range is achieved simply by varying the SPOPO cavity delay without adjustment of any other parameters such as the PPLN crystal temperature, BIBO phase-match angle, or pump wavelength.

The generation of widely tunable high-repetition-rate femtosecond pulses across the entire visible range of 480-710 nm by developing a SPOPO based on BIBO, and achieved wavelength extension to 250-350 nm in the UV using intracavity SHG of the visible signal pulses in BBO, has been reported. Combined with the tunability of the fundamental Ti:sapphire laser, the approach provides an exceptionally versatile and continuously tunable source of high-repetition-rate (76 MHz) femtosecond pulses from the UV to near-IR across 250-1000 nm.

BIBO possesses a unique combination of excellent properties for broadband parametric amplification when pumped near 800 nm in collinear geometry. Higher order dispersion terms determine in this case the parametric gain bandwidth which can be extremely broad. In addition, the group velocity matching with the pump ensures long interaction lengths and high efficiency even for femtosecond pulse durations. Hence, BIBO is a very promising candidate for a wide range of femtosecond down-conversion schemes based on Ti:sapphire laser pump sources. Several such schemes in the high-power regime at a repetition rate of 1 kHz have been realized (Fig. 1).

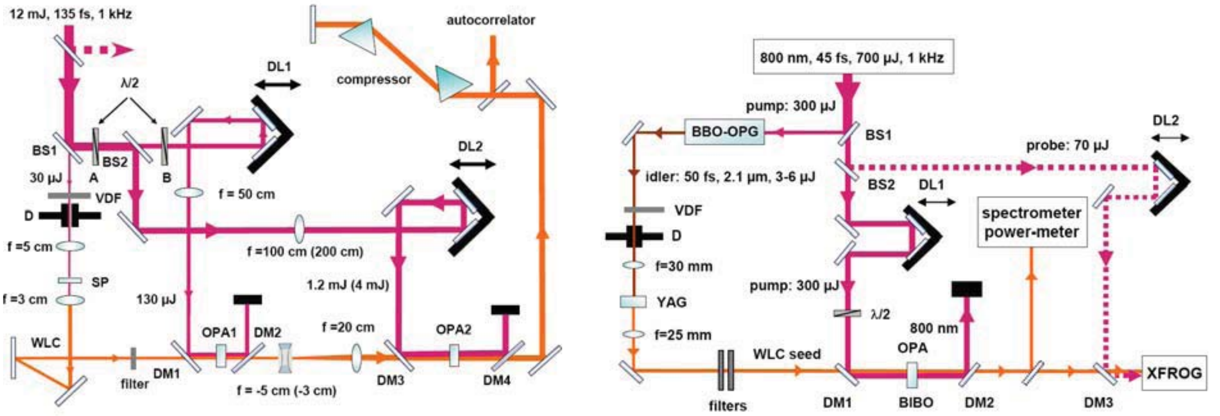

Fig. 1. Schematics of the experimental set-ups of high-power optical parametric amplification based on two stages with BIBO crystals that yields pulse energies as high as 1.1 mJ (signal plus idler), left, and ultra broadband continuum amplification, reaching spectral bandwidths of up to ~100 THz, right. Both schemes are pumped near 800 nm at a repetition rate of 1 kHz.

The BIBO crystal has been implemented in a 800 nm pumped femtosecond two-stage type-II OPA and demonstrated efficient and tunable operation at 1 kHz with certain advantages (extension to the 3 µm spectral range) over BBO. The shortest pulses obtained were of the order of 100-110 fs. Using two BIBO crystals (type-II and type-I) in a two stage femtosecond OPA it was possible to increase the output energy roughly 5 times in comparison to previous work with BBO at 1 kHz repetition rate (Fig. 1, left). The maximum energy obtained for a signal wavelength of 1200 nm was 1.1 mJ (signal plus idler) and the tunability extended from 1.1 to 2.9 µm. Using a two stage broadband (type-I – type-I) BIBO OPA with WLC seeding, it was possible to generate sub-30 fs signal pulses near 1300 nm after compression, at energies exceeding 200 µJ, by pumping with 150-fs pulses near 800 nm at 1 kHz. The corresponding idler pulses near 2.3 µm had a duration of 55 fs without compression and energy exceeding 100 µJ.

Ultra-broadband optical parametric amplification (Fig. 1, right) and generation has been realized in the near-IR with WLC energy as high as 50 µJ in the case of OPA and 15 µJ in the case of the simpler OPG scheme. These values correspond to internal conversion efficiency of 20% and 7%, respectively. In all cases the integral pulse durations achieved are in the sub-100-fs range and the spectral extension covers an octave. This is the first time such WLC has been generated or amplified by a second order nonlinear process on the femtosecond time scale. Amplification in a second stage increased the output energy to above 100 µJ.

The unique versatile nonlinear optical properties of BIBO combined with the frequency conversion methods described here provide efficient and widely tunable ultrafast sources across the UV, visible and near-IR, offering the advantages of simplicity, practicality, high average power, high intensity and pulse energy, and convenient operation at room temperature.

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