High-energy, sub-30 fs near-IR pulses from a broadband optical parametric amplifier based on collinear interaction in BiB_3O_6

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We report efficient generation of tunable femtosecond pulses in the near IR using a two stage, white-light seeded, collinear, femtosecond optical parametric amplifier (OPA). The OPA, based on BiB_3O_6 crystal in both stages and pumped at 807 nm by a 1 kHz Ti:sapphire laser amplifier, provides sub-30 fs signal pulses after compression with energies exceeding 200 μJ, which corresponds to fivefold pulse shortening and ~30% internal conversion efficiency in the second stage considering 150 fs pump pulses with 1.5 mJ energy. The corresponding idler pulses with more than 100 μJ have sub-60 fs duration without compression. The first stage alone is capable of producing sub-20 fs pulses near 1400 nm at the microjoule level without using any compression. © 2009 Optical Society of America

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High-energy, ultrashort pulses in the near IR are of special interest for a variety of applications in nonlinear optics and time-domain spectroscopy. Generation of pulses as short as 14.5 fs at 1.5 μm and with energies of about 12 μJ (signal plus idler) using a β-BaB_2O_4 (BBO) crystal has been reported [1]. Further scaling of such a system is limited by the damage threshold of the fiber used for the spectral broadening of the pump pulses in the compressor stage. Also 200 μJ, 15 fs phase-stable pulses at 1.5 μm were produced by difference-frequency generation of a hollow-fiber broadened supercontinuum followed by two-stage BBO-based optical parametric amplification pumped by 50 fs pulses. Beside the complex setup, the need to generate broadband supercontinuum in this work makes the availability of short pump pulses (not much longer than 50 fs) essential [2]. Furthermore, in a noncollinear, blue pumped optical parametric amplifier (OPA) sub-50 fs idler pulses tunable across the spectral range of 900–1600 nm with microjoule-level energy [3,4] have been generated.

In all of the above experiments BBO is the crystal that performs as the nonlinear medium. Recently a relatively new nonlinear crystal, bismuth triborate, [BiB_3O_6 (BIBO)] has attracted a lot of attention because of its efficient performance for light conversion applications in the visible and near-IR spectral regions [5–8]. The unique property of BIBO for having ultrabroadband spectral acceptance in the near IR for type I ($e \rightarrow o+o$) phase matching (PM) inside an xz optical plane under pumping at wavelengths near 800 nm has recently been the subject of a number of experiments, including a mode-locked Ti:sapphire laser pumped femtosecond BIBO optical parametric oscillator [9], ultrabroadband parametric generation [10], and ultrabroadband parametric amplification of white-light continuum (WLC) in the near IR [11]. This property has been investigated in detail, and it has been shown that in parametric generation and amplification with near 800 nm pump, for collinear interaction the parametric gain becomes ultrabroad toward degeneracy, and simultaneously the group-velocity mismatch (GVM) with the pump tends to zero [10]. Also generation of high-energy pulses in the near IR using a BIBO-based OPA system has been previously demonstrated by intentionally using a type II crystal in the first stage to limit the gain bandwidth but allow tuning in the range of 1.1–2.9 μm for the signal and idler [12]. This system produced 200-fs-long pulses [12], while the bandwidth of the signal was limited to about 40 nm.

In this Letter, we report on efficient generation and compression of high-energy pulses near 1300 nm by taking advantage of the large gain bandwidth of BIBO when pumped by near 800 nm pulses [10]. Under pumping by 150 fs pulses, signal pulses as short as 25 fs with energies exceeding 200 μJ are generated. By applying type I BIBO in the two stages of an OPA system, broadband amplification of the WLC is realized. The idler pulses near 2300 nm have a duration of 55 fs without compression.

The configuration of the two-stage collinear BIBO femtosecond OPA is shown in Fig. 1. The OPA is pumped by the fundamental of a regenerative–multipass Ti:sapphire amplifier at 807 nm. The laser provides up to 12 W of average power at 807 nm in ~150 fs pulses with 1 kHz repetition rate. The crystals applied in both stages are 3 mm long, uncoated BIBO cut at $\theta=11.4°$ for type I ($e \rightarrow o+o$) PM inside the optical xz plane. The optimized crystal length in both stages is important to satisfy the efficient amplification and minimum contribution to the chirp content of the pulses.

Using the beam splitter BS1, about 1.8 mJ of the fundamental pulse energy is divided into two parts; the main part is reserved for pumping the two OPA stages, and a small part is directed to the WLC gen-

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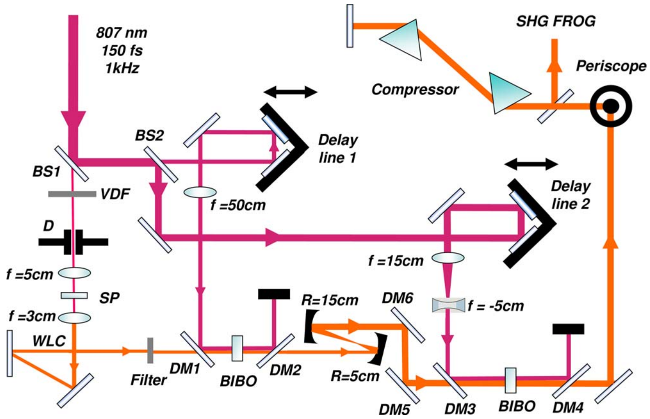

Fig. 1. (Color online) Configuration of the two-stage, WLC-seeded OPA based on type I ($e \rightarrow o + o$) phase matching in BIBO crystal. BS, beam splitter; D, diaphragm; VDF, variable density filter; SP, sapphire plate; WLC, white-light continuum; DM, dichroic mirror.

eration line. After passing through a variable density filter (VDF) and a diaphragm, less then 20 μJ of the pulse energy is focused onto a 2-mm-thick sapphire plate using a lens with $f = 50$ mm. A second lens with $f = 30$ mm, which is mounted on a translation stage after the sapphire plate, is used for imaging the WLC on the first-stage BIBO crystal. The near-IR part of the WLC for seeding the first OPA stage is selected using a thin long-pass filter. The main part of the fundamental power, which is reflected from BS1, is divided by another beam splitter, BS2, into two parts for pumping the two stages of the OPA. About 200 μJ of the fundamental pulse energy is focused on the first BIBO using an $f = 500$ mm lens. The position of the first-stage BIBO crystal is close to the focal point of the lens but still far enough from it to avoid optical parametric generation (OPG). The dichroic mirrors DM1–DM4, highly reflective ($R > 99\%$) for the pump and highly transmitting ($T > 90\%$) for the signal and idler wavelengths, are used for collinear recombination and separation of the beams. The characterization of the generated signal and idler pulses was performed using the second-harmonic generation, frequency-resolved optical gating (SHG FROG) technique [13].

Spectral and temporal behavior of the WLC amplified in the first stage strongly depends on the signal wavelength. For $1150 < \lambda < 1300$ nm well-defined spectra with 30–100 nm width, increasing with wavelength, and pulse energies exceeding 5 μJ are achieved. Starting from 70 fs near 1150 nm, the signal pulses shorten down to 40 fs by increasing the wavelength, which can be expected because of the better group-velocity matching [10]. At longer wavelengths, $\lambda > 1300$ nm, the signal behavior changes dramatically because of the WLC energy decrease. To produce sufficient signal energy for seeding the second OPA stage the pump intensity in the first stage should be increased by moving the crystal closer to the focal point and because of the broader spectral acceptance of BIBO in this range, cw tuning is not possible anymore, and a broad spectrum with little tunability only around ~1400 nm is selected by the crystal. At this wavelength the negligible group-velocity dispersion (GVD) of BIBO (≈33 fs^2/mm) results in near transform-limited signal pulses with a duration as short as ~18 fs without using any compression.

For the amplification of the signal pulses generated from the first stage, about 1.6 mJ of the pump pulse energy is sent to the second OPA stage. The type I BIBO crystal in the second stage has an aperture of 10 mm × 10 mm. By using a 3:1 Galilean lens telescope in the pump beam path, the pump diameter is expanded to about 8 mm to avoid crystal damage. Using an all-reflective 1:3 telescope in the signal beam path, the seed beam diameter is adjusted to about 6 mm to achieve higher conversion. To avoid the complications arising from the simultaneous seeding with signal and idler pulses in the second stage, two dichroic mirrors, DM5 and DM6, which have high reflectivity ($R > 99\%$) for the signal and high transmission ($T > 90\%$) for the idler, are used to suppress the idler. The amplified signal pulses in the second stage nearly follow the behavior of the seed pulses from the first stage. Typical spectra of the amplified signal pulses after the second stage are shown in Fig. 2. As it can be seen, for wavelengths shorter than 1200 nm where still the interaction is not in the ultrabroadband regime and the spectral acceptance bandwidth is limited, signal pulses with well-defined spectra and spectral bandwidths of about 30 nm at FWHM are generated. For the signal pulses in the range of $1200 < \lambda < 1300$ nm, the spectral acceptance bandwidth starts growing rapidly and the spectral bandwidths are about 80–120 nm, which support sub-30 fs transform-limited pulses. Across the tuning range of $1150 < \lambda < 1300$ nm, more than 400 μJ (signal plus idler) pulse energy is produced in the second stage, corresponding to an internal conversion efficiency of 30% in this stage.

To compress the signal pulses we applied a prism-pair compressor in a double-pass configuration consisting of two Brewster-angled prisms of SF11 with a separation of 50–70 cm depending on the wavelength. Figures 3(a) and 3(b) show the experimental 128 × 128 points SHG FROG trace and the corresponding retrieved temporal intensity and phase profiles of the measurement, respectively, for a typical

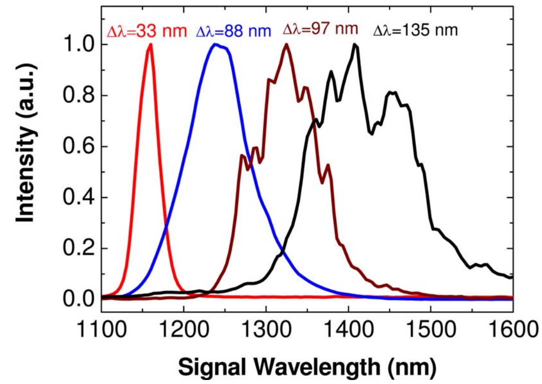

Fig. 2. (Color online) Typical spectra of the amplified near-IR signal pulses after the second stage across the tuning range.

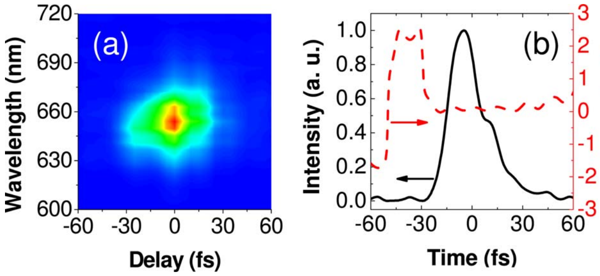

Fig. 3. (Color online) Typical FROG measurement of the compressed signal pulse with a FROG error of 0.009 (128 $\times$ 128 pixels). (a) Amplitude of measured FROG trace (128$\times$128 pixels). (b) Retrieved intensity and phase as a function of time. The time duration of ~25 fs corresponds to a time-bandwidth product of 0.31.

compressed signal pulse near 1300 nm (FROG error 0.009). The SHG was performed using a 25-μm-thick BBO crystal cut at $\theta=44°$ for type I ($o+o\rightarrow e$) PM. The retrieved pulse duration of 25 fs (FWHM) with a time-bandwidth product of 0.31 is close to the transform limit, which is evident from the almost constant phase in time.

Adjusting both stages for 1400 nm at reduced pump intensity in the second stage (obtained by expanding the pump beam), signal pulses as short as 35 fs with 50 μJ (signal plus idler) energy were achieved without compression. However, at this wavelength we observed that by increasing the pump intensity an OPG contribution will appear that results in temporal broadening of the signal pulse to 50 fs at the level of 100 μJ (signal plus idler) energy. The reason for such an increase of the OPG at this spectral region compared to shorter wavelengths is the decrease in the WLC energy seeding the first stage and consequently the lower seed energy supplied to the second stage. One solution to this problem in order to extend the tunability of the present OPA can be the use of more stages for signal amplification, but this obviously complicates the whole setup.

We also characterized the idler pulses generated in the second stage in the spectral range characterized by high output energy. A typical SHG FROG measurement at ~2300 nm is shown in Fig. 4, presenting an idler pulse with a duration of 55 fs and a spectral width of 160 nm, which corresponds to a time-bandwidth product of 0.5. The idler pulses carry negative chirp content and cannot be further compressed by a normal prism pair compressor.

In conclusion, we have demonstrated a two-stage, WLC-seeded OPA capable of producing sub-30 fs pulses near 1300 nm. Using two BIBO crystals based on type I collinear phase matching, the OPA showing 1 order of magnitude energy-scaling generates near-IR signal pulses at 1 kHz repetition rate with

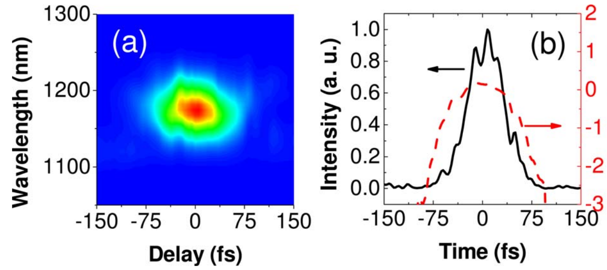

Fig. 4. (Color online) Typical FROG measurement of the uncompressed idler pulse. (Explanations similar to Fig. 3, only the FROG error is 0.008). The pulse duration is ~55 fs, corresponding to a time-bandwidth product of 0.5.

an energy exceeding 200 μJ and duration as short as 25 fs under pumping by 150 fs pulses, presenting significant pulse shortening. The short temporal width and near-transform-limited characteristics of the pulses combined with high output energies can make this device an attractive tool for a wide range of applications in nonlinear optics and spectroscopy. Further energy scaling of the system by applying higher pump pulse energies with increasing the number of the amplification stages should result in pulses with higher energy across the near IR.

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