Broadband, rapidly tunable Ti:sapphire-pumped BiB_3O_6 femtosecond optical parametric oscillator

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We report a femtosecond optical parametric oscillator (OPO) based on the nonlinear material BiB_3O_6 (BIBO) pumped directly by a Kerr lens mode-locked Ti:sapphire laser. Using a 1.5 mm long BIBO crystal cut at $\theta = 11.4°$ for collinear type I ($e \to o + o$) phase matching in the xz optical plane, femtosecond signal pulses across 1.4–1.6 μm, and idler pulses across 1.6–1.87 μm spectral range are generated, limited by the reflectivity bandwidth of the OPO mirrors. The high nonlinear gain and large spectral acceptance for type I interaction in the xz plane of BIBO permit rapid and continuous tuning across the entire range by simple fine adjustment of OPO cavity delay or through small changes in the pump wavelength, without varying any other parameters. Additionally, owing to the near-zero group velocity mismatch and dispersion, the OPO supports broad spectrum as wide as 33 nm, which results in self-compressed signal pulses. For 150 fs pump pulses, signal pulses with durations down to 106 fs with a time-bandwidth product of 0.48 are obtained without the need for intracavity dispersion compensation.

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Bismuth triborate, BiB_3O_6 (BIBO), is a nonlinear material with unique optical properties for frequency conversion in the visible and UV [1,2]. It combines the advantages of UV transparency and high damage threshold, as in β-BaB_2O_4 and LiB_3O_5, with enhanced optical nonlinearity, as in $KTiOPO_4$. The optical transmission of BIBO extends from ~2.7 μm in the IR down to ~280 nm in the UV, and as a biaxial crystal, it offers versatile phase-matching (PM) characteristics and broadband angle tuning at room temperature. The effective nonlinear coefficient of BIBO is typically >3 pm/V, which is larger than that of β-BaB_2O_4 and LiB_3O_5, and comparable to that in $KTiOPO_4$. Such a combination of properties has made BIBO a highly attractive material for frequency conversion of cw and pulsed laser radiation into the visible and UV. In the ultrafast domain, we have also demonstrated highly efficient single-pass second-harmonic-generation (SHG) of tunable high-repetition-rate femtosecond [3] and picosecond [4] pulses into the blue using BIBO. We also reported a femtosecond optical parametric oscillator (OPO) based on BIBO for the visible, pumped by the second harmonic of the Kerr lens-mode-locked (KLM) Ti:sapphire laser in the blue [5]. Here, we describe a femtosecond OPO based on BIBO for the near IR, pumped by a KLM Ti:sapphire laser. To our knowledge, this is the first femtosecond OPO based on BIBO pumped directly by a KLM Ti:sapphire laser, which also offers practical features of simplified, rapid, and continuous tuning across the full range using cavity delay detuning without adjustment of any other parameters or realignment of the OPO resonator during tuning.

Owing to the monoclinic symmetry, BIBO can provide different types of PM in the three optical planes. For optical parametric processes pumped at 800 nm, type I ($e \to o + o$) PM with wide tuning in the xz optical plane is available, with $d_{eff} \sim 2.9$ pm/V. In addition, the spectral acceptance bandwidth becomes very large since the group velocity mismatch (GVM) between signal and idler pulses is very small and vanishes near degeneracy [6]. In particular, for a signal wavelength range of 1400–1600 nm, the pump-signal and pump-idler GVM are very close and less than 11 fs/mm, giving rise to a signal–idler GVM less than 1.2 fs/mm. Moreover, the group velocity dispersion (GVD) is varying from 35 fs^2/mm to nearly zero close to degeneracy. These features indicate excellent performance of BIBO for broadband generation in the near IR under type I ($e \to o + o$) PM in the xz optical plane.

As an example of this potential, ultrabroadband continuum amplification of white light has been achieved in BIBO pumped at 800 nm [6,7]. We also exploited this feature to achieve tunable femtosecond pulse generation in the red by internal doubling of a periodically poled $LiNbO_3$femtosecond OPO in BIBO cut for type I ($o + o \to e$) SHG in an xz plane [8]. Here we exploit the favorable properties of BIBO for type I ($e \to o + o$) interaction in an xz plane to demonstrate a femtosecond OPO in the near IR, synchronously pumped directly by a KLM Ti:sapphire laser.

The configuration of the OPO is shown in Fig. 1. The pump laser provides transform-limited 150 fs pulses at 76 MHz, tunable around 800 nm. After the optical isolator,

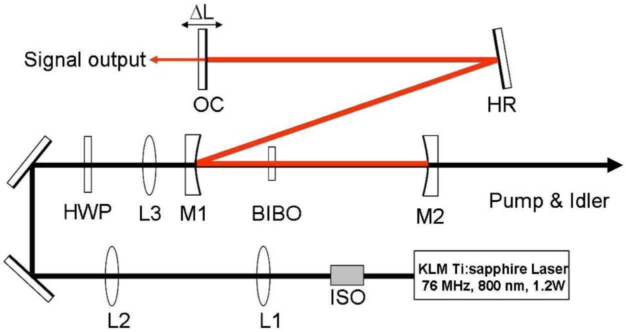

Fig. 1. (Color online) Schematic of the Ti:sapphire-pumped OPO based on the xz-cut BIBO with type I ($e \to o + o$) interaction, for the generation of femtosecond pulses with rapid tuning in the near IR.

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an average pump power of 1 W is available. The OPO uses a 1.5 mm long BIBO crystal cut for collinear type I ($e \rightarrow o + o$) PM in the xz optical plane at an internal angle $\theta = 11.4°$ ($\phi = 0°$) at normal incidence. The end faces have broadband antireflection (AR) coating ($R < 1\%$) for the pump over 800–840 nm and for a signal over 1400–1600 nm. A set of lenses $L1$ ($f = 5$ cm), $L2$ ($f = 15$ cm), and $L3$ ($f = 8$ cm), AR coated ($R < 1\%$) at 800 nm are used to focus the pump to a beam waist radius $w_o \sim 25\,\mu$m inside the BIBO crystal. A half-wave plate provides extraordinary pump polarization. The OPO is configured in a standing-wave cavity comprising two concave reflectors M_1 and M_2 ($r = 100$ mm), one high reflector (HR) plane folding mirror and one plane mirror acting as a 5% output coupler (OC), mounted on a translation stage to allow variation of the cavity length with micrometer precision. The mirrors HR, M_1, and M_2 are highly reflecting ($R > 99\%$) over 1.45–1.55 μm and highly transmitting ($T > 90\%$) at 800 nm.

Figure 2 presents the type I ($e \rightarrow o + o$) PM diagram in an xz plane, showing the significantly broad bandwidth for a fixed PM angle, θ. In particular, the normalized gain coefficient remains at maximum for the wide-signal wavelength range of 1.2–1.6 μm. As a result, the OPO can be tuned within this range without the need for adjusting the PM angle. This was verified experimentally, as shown in Fig. 2, where the recorded tuning data for signal and idler are included in the plot. For tuning, we used two independent mechanisms, both resulting in signal coverage across the entire range of 1.44–1.58 μm, as shown in Fig. 3. In the first method, rapid and continuous tuning was achieved by adjustment of the cavity delay without varying any other parameters, where the BIBO crystal was maintained at a fixed angle near normal incidence (~11.2°), and the pump wavelength remained fixed at 800 nm. The static cavity-length tuning is shown in Fig. 3(a), and the corresponding output power through the 5% OC is shown in Fig. 3(b). In the second method, continuous tuning across the full range could be obtained by changing the pump wavelength over a small range, while keeping all other parameters including the crystal angle, cavity delay, and OPO alignment unaltered.

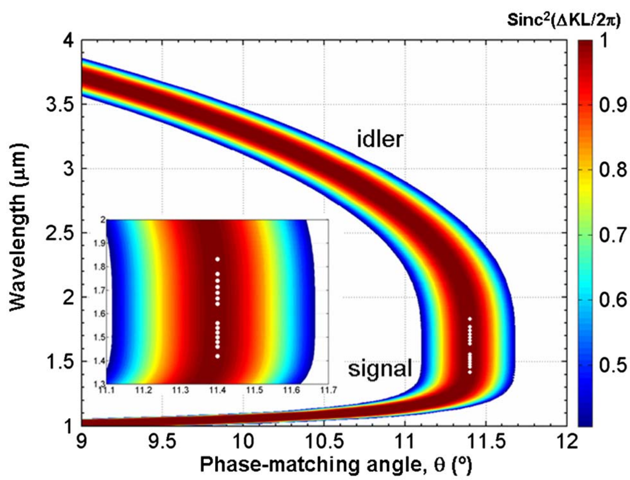

Fig. 2. (Color online) PM diagram showing the variation of normalized parametric gain coefficient, $\mathrm{sinc}^2(\Delta kL/2\pi)$, in the limits of $-\pi < \Delta kL < \pi$, where $L = 1.5$ mm. Inset: signal and idler tuning data obtained by changing the cavity length.

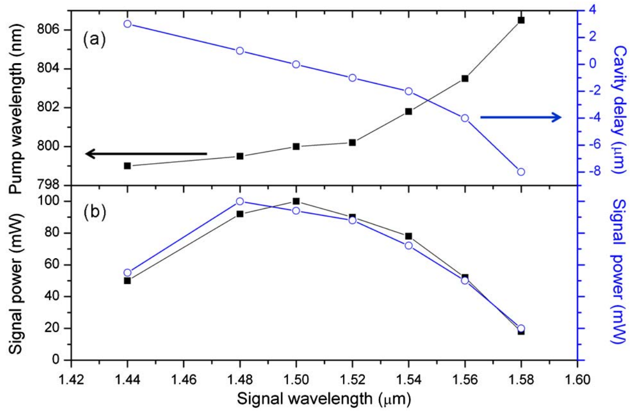

Fig. 3. (Color online) (a) Double static tuning by cavity length (circles) and pump detuning (squares) versus signal wavelength. (b) Typical variation of the generated signal average power across the tuning range by changing the cavity delay (circles) and pump wavelength (squares).

The static pump wavelength tuning is also shown in Fig. 3(a), and the corresponding output power through the 5% OC is shown in Fig. 3(b). Therefore, one can see that the OPO can be tuned across 140 nm by varying the OPO cavity length over 11 μm or by tuning the pump over 7.5 nm. Moreover, the performance of the OPO output power across the tuning range remains the same in both cases, as clearly shown in Fig. 3(b). For a fixed pump wavelength, the cavity-length tuning avoided the need for realignment of the OPO, resulting in simplified and rapid tuning. The total obtained tuning range of 1.44–1.58 μm for the signal, with a corresponding range of 1.62–1.80 μm for the idler, was limited by the fall in reflectivity of the OPO mirrors at the signal wavelength and the crystal coating. With optimized broadband coatings, we expect to be able to exploit the large PM bandwidth, shown in Fig. 2, to provide continuous coverage in the signal and idler from ~1 μm to the IR transmission cutoff in BIBO, above ~2.6 μm, using rapid static tuning.

The signal power extracted through the 5% OC reaches 100 mW at the maximum available pump power of 1 W, corresponding to a conversion efficiency of 10%. In the absence of more suitable OCs, no attempt was made to maximize the extracted power. The pump depletion is 40% at the maximum input pump and the typical pump power threshold for the OPO with the 5% OC is 325 mW. The absence of saturation, no evidence of optical damage, and quite a moderate level of depletion suggest the possibility of increasing the output power by increasing the pump power as well as optimizing the output coupling.

Spectral measurements for the pump and the OPO output signal pulses were obtained using an optical spectrum analyzer, while temporal characterization was performed using fringe-resolved intensity autocorrelation based on two-photon absorption in GaAsP and Si photodiodes for the signal and pump, respectively. The results are shown in Fig. 4. A typical autocorrelation profile and spectrum of the pump at 800 nm is shown in Fig. 4(a), indicating 144 fs pulses and thus confirming a time-bandwidth product of 0.47 (assuming sech^2 pulse shape). In the absence of dispersion compensation in the OPO, spectral bandwidths for the signal pulses range from ~20 up to ~40 nm, but the pulses are chirped across most of the tuning range.

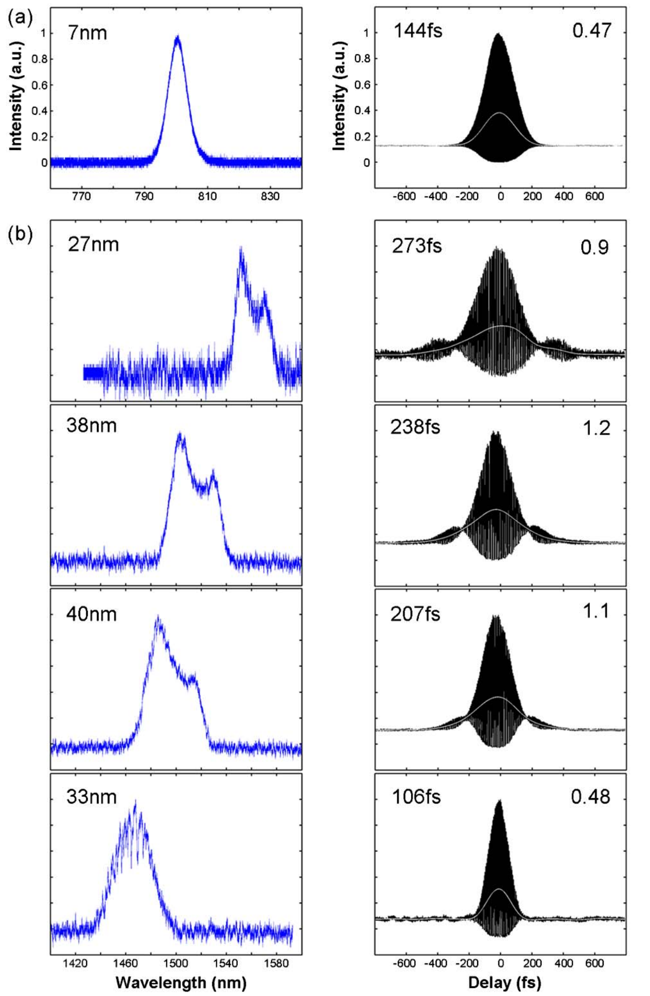

Fig. 4. (Color online) Spectra (left column) and intensity autocorrelation traces (right column) of (a) the pump pulses at 800 nm and (b) the OPO signal pulses across the tuning range.

However, the signal spectrum showed a smoother profile in the vicinity of 1.46 μm, while maintaining a broad bandwidth of 33 nm. Pulse durations from 206 fs to 273 fs were measured within the tuning range 1.50–1.58 μm, with time-bandwidth products from 0.9 to 1.2, implying near transform-limited pulses. The variation in pulse duration across the tuning range is consistent with the variation in the corresponding spectra, where shorter wavelengths exhibit broader spectra, and consequently, shorter pulse durations. Surprisingly, the pulses around 1.46 μm showed no evidence of chirp, and the duration was as short as 106 fs, being near transform limited with a time bandwidth of 0.48 and shorter than the pump pulse. It is worthwhile to note that the spectrum between 1.46 and 1.48 μm was even broader than 40 nm, but extremely unstable, making impossible reliable characterization. Therefore, the tuning range was divided into two regions with different performance: in one region, from 1.50–1.58 μm, where pulses are affected by chirp and the spectrum is broad; in another region, below 1.48 μm, where the pulses are smooth and self-compressed.

This unusual self-compression effect has been previously observed in a visible OPO based on β-BaB_2O_4 pumped by the second harmonic of a Ti:sapphire laser [9], and attributed to cascaded second-order effects [10] when the parametric signal generation and SHG occur simultaneously. Indeed, with the crystal used in our experiment, collinear SHG in the neighborhood of 1.5 μm is achieved within the bandwidth of a 1.5 mm crystal at an internal angle of 11.2°, with a phase-mismatch of $\Delta k = 1.85\,\mathrm{mrad}\cdot\mu\mathrm{m}^{-1}$, and a corresponding normalized parametric gain still at 50%. Furthermore, we observed weak red generation when the OPO was tuned around the pulse compression range. We thus expect that the use of suitable chirped mirrors with controlled GVD and improved optics to extend the tuning range will enable a generation of even shorter pulses, making use of the broadband spectrum supported by this OPO.

In conclusion, we have demonstrated a Ti:sapphire-pumped femtosecond OPO based on BIBO, providing wide, continuous, and rapid static tuning across 1.4–1.6 μm by only varying the cavity delay or the pump wavelength. The use of collinear type I ($e \to o + o$) PM with a pump wavelength range in the vicinity of 800 nm leads to a large spectral acceptance bandwidth, resulting in a vanishing GVM between signal and pump pulses, and enabling the generation of near-transformed signal pulses down to 106 fs. The obtained tuning range is currently limited only by the available mirrors and can be readily extended using more suitable coatings. The static cavity delay tuning could be attractive for rapid wavelength scanning or modulation using piezoelectric control of the OPO cavity length. To our knowledge the rapid, broadband, and static tuning features of BIBO exploited here have not been previously demonstrated in femtosecond OPOs directly pumped by the Ti:sapphire laser based on other birefringent materials such as β-BaB_2O_4, LiB_3O_5, or $KTiOPO_4$ and its isomorphs.

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