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## Fast Track Communication

# High efficiency, high energy, CEP-stabilized infrared optical parametric amplifier

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## Abstract

A high efficiency, tunable, carrier-envelope-phase (CEP) stabilized near-infrared optical parametric amplifier (OPA) is demonstrated with just a single BBO crystal. A white-light continuum produced by a CEP-stabilized laser is seeded into the two stages of the type II OPA system. We achieved a pump-to-signal conversion efficiency of 34% with a single nonlinear crystal. To our knowledge this is the highest conversion efficiency reported in broadband optical parametric amplification, using the two stages. This work demonstrates a compact way to for tunable femtosecond pulses with CEP stabilization.

Keywords: ultrafast nonlinear optics, parametric oscillators and amplifiers, ultrafast lasers, ultrafast technology

(Some figures may appear in colour only in the online journal)

## 1. Introduction

Powerful carrier-envelope-phase (CEP) stabilized pulses [1] that are tunable in the visible and/or near infrared spectral range are of special interest due to potential applications to nonlinear optics, ultrafast spectroscopy [1] and attosecond spectroscopy [2, 3]. Attosecond spectroscopy requires such pulses for the reproducible generation and precision measurement [4] of isolated attosecond pulses for pump-probe experiments. To this end, the higher pulses appear desirable, allowing the higher photon energy of the attosecond pulse according to the  $I\lambda^2$  scaling of the cut-off energy of high-order harmonics (HOH), where  $I$  is the peak intensity and  $\lambda$  is the carrier wavelength [5]. Optical parametric amplification

(OPA) represents the most promising approach to achieving this goal [6–17].

At present, high energy pulses are generated mainly by non-collinear optical parametric amplifiers (NOPA) in  $\beta$ -barium borate (BBO) crystals [18–22] or collinear optical parametric amplifier (COPA) in  $\text{BiB}_3\text{O}_6$  (BIBO) crystals [23, 24]. There are several ways to generate the broadband radiation needed to seed the OPA for powerful few-cycle pulse production. These include white light continuum (WLC) generation in a single filament in sapphire [18, 19], idler wave generation in a non-collinear OPA, difference-frequency generation (DFG) with the supercontinuum emerging from a hollow-core fiber [21, 22], a sapphire plate [23, 24], PPLN [25] or YAG [26]. Such a broadband seed pulse has then been amplified by two or three OPA stages in



### 3. Results and discussion

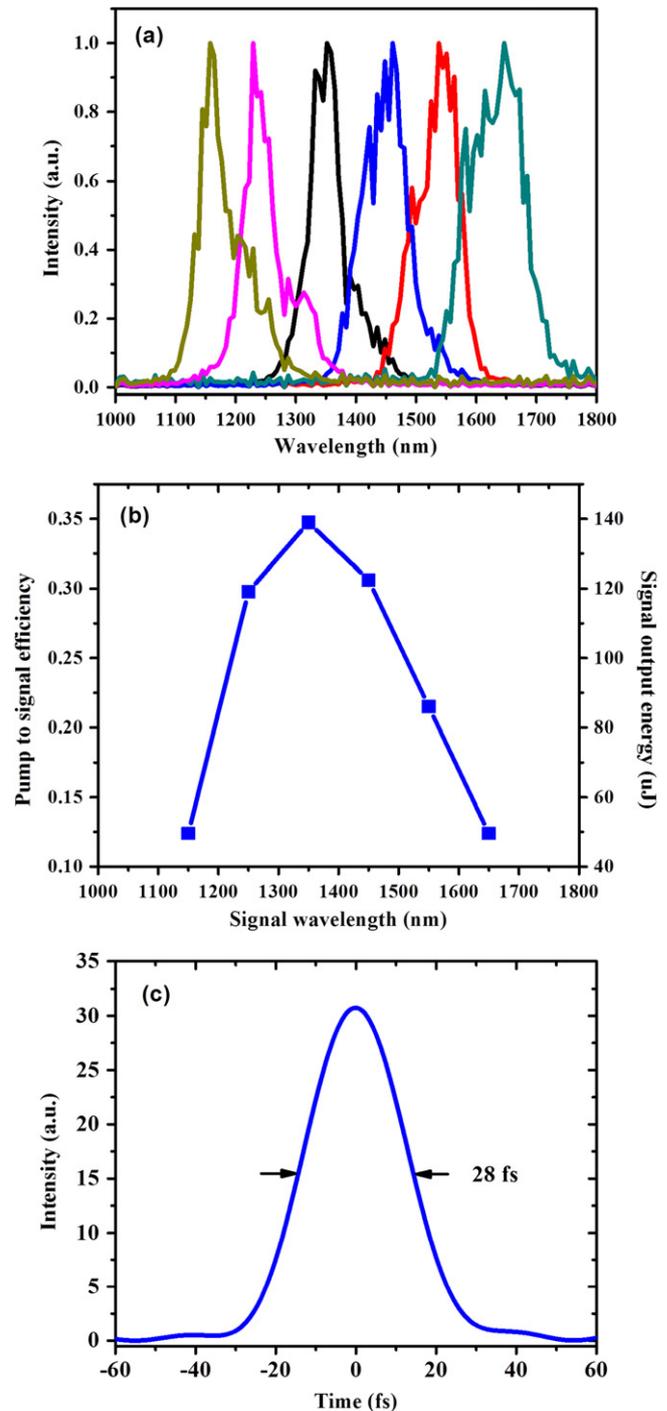
An amplified signal energy of  $3 \mu\text{J}$  is obtained in stage 1. We expand and collimate the seed beam with a Kepler 1:3 telescope to match the beam size of the seed and the pump pulses on the crystal for stage 2. The idler wave is blocked by a beam dump when it is separated from seed and pump laser after propagation. Then the collimated signal output from stage 1 is injected into stage 2 for further amplification, in which the signal and pump light are incident on the same BBO in the opposite direction and parallel to each other as in stage 1. The optical path in the BBO is shown by the inset of figure 1. About  $407 \mu\text{J}$  is sent to pump the stage 2 by the second beam splitter. To obtain the best spatial beam quality for the output pulse, the power density on the crystal is optimized by a down-collimator with a ratio of 3:1. We carefully optimize the spatial and temporal match by adjusting the crystal phase matching angle and the time delay for pump pulses in order to obtain a stable amplification in the saturation regime. We measure as much as  $138 \mu\text{J}$  of amplified signal energy directly after the nonlinear crystal that corresponds to the pump-to-signal conversion efficiency of 34%.

In the stage 2, the tunable signal pulse is amplified and signal spectrum can be tuned from 1100 nm to 1700 nm by changing BBO phase matching angle, (see figure 2(a)). Figure 2(b) is the conversion efficiency curve corresponding to different signal wavelengths measured by changing phase matching angle. The conversion efficiency varies from 12% around 1100 nm and 1700 nm to 34% around 1350 nm.

The pulse duration of OPA output is determined by the pump pulse width. The pulse is characterized by spectral phase interferometer for the direct electric field reconstruction (SPIDER) method. Figure 2(c) shows the reconstructed pulse in the time domain, which has a full width at half maximum (FWHM) duration of 28 fs around 1350 nm and is comparable to a pump pulse duration of 25 fs FWHM. The result indicates that the amplified pulse duration does not change relative to the pump pulse duration in the IR wavelength range.

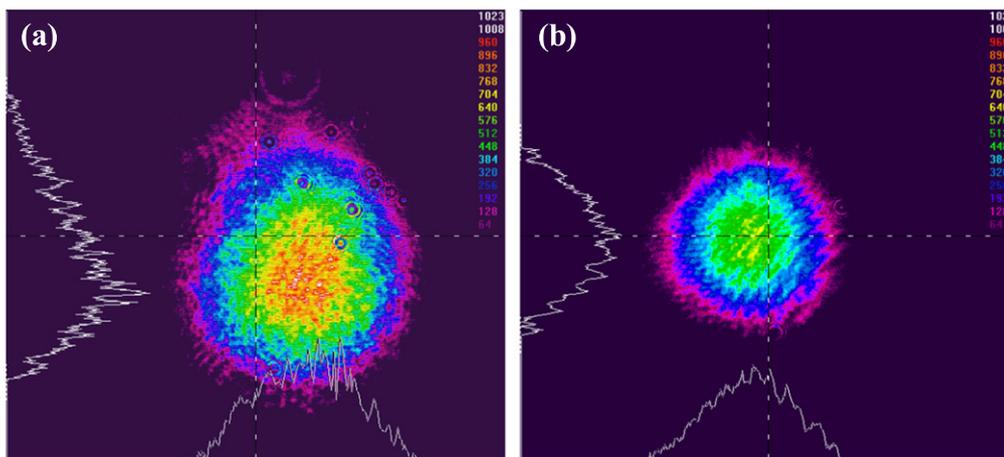
It is necessary to restrain the superfluorescent amplified signal (SAS) in order to obtain a good signal beam quality in stage 2. To do so, the pump intensity for the stage 2 is controlled at  $250 \text{ GW cm}^{-2}$ . Simultaneously, we found that the optimization of timing overlap between the signal and pump is important to improve beam quality. Figures 3(a) and (b) show the amplified signal beam quality at different times of timing overlap. The bad beam quality in figure 3(a) is due to imperfect timing overlap with a strong SAS. A precise pump and signal time overlap removes most of the SAS and obtains a perfect beam quality (see figure 3(b)).

In the current tuning range of the spectrum, the sign of the relative group velocity of the signal wave with respect to the pump is opposite to that of the relative group velocity of the idler wave with respect to the pump. The simulation study shows that the exponential growth of the signal is preserved for a long length of crystal [40]. This fact relaxes the restriction on the crystal length (the typical separation length of 2 mm for 790 nm pumping) due to group-velocity

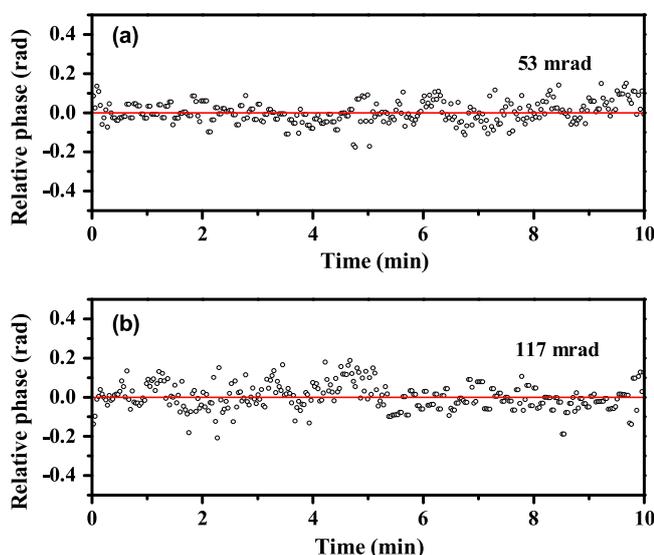


**Figure 2.** (a) (Normalized) spectrum change of the optical parametric amplifier by changing BBO phase matching angle. (b) The pump to signal conversion efficiency curve in the final OPA stage. The highest conversion efficiency is 34% for the signal pulses at 1350 nm. (c) Reconstructed pulse in the time domain around 1350 nm measured by SPIDER method.

mismatch. A longer crystal can result in a higher conversion efficiency. Hence a 3 mm thick BBO is selected, which has a minimal effect on pulse broadening of the seed laser and yet results in a high conversion efficiency. The same gain wavelength in a two-stages NOPA (because the angle between the pump and the signal light as well as between the



**Figure 3.** (a) Final amplified pulse profile with SAS; (b) final amplified pulse profile with perfect temporal overlap.



**Figure 4.** CEP jitter fluctuation over time (a) seed light CEP jitter is 53 mrad (rms); (b) the final amplified pulse CEP jitter is 117 mrad (rms).

crystal and the pump are maintained the same as shown in the inset of figure 1) also contributes to the high conversion efficiency. Excellent quality of pump and signal beams as well as their spatial and temporal matching are also important prerequisites for the high efficiency obtained.

To investigate the effect of NOPA on maintaining a stable CEP in the amplified output, we use an  $f-2f$  interferometer and measure the CEP jitter of the seed as well as the amplified pulse after the stage 2. The  $f-2f$  interferometric spectra are recorded with a time interval of 10 min (see figure 4). The linear Fourier-transform spectral interferometry algorithm analysis of the spectral interference fringes with 50 ms time shows that the CEP jitter is 53 mrad (rms) for seed pulse and 117 mrad (rms) for amplified signals. Hence, the CEP jitter is increased by approximately a factor of two in the OPA process. The result shows that the CEP hybrid control method (based on the active control of seed pulse CEP and the passive control of amplified pulse CEP) is feasible and

effective for CEP controlled infrared NOPA. For practical applications, we need the CEP to be kept stable for hours. Since the seed pulse CEP is actively controlled in this hybrid control scheme, we can easily set up a slow loop to control output pulse CEP for a longer period of time. This is the advantage of the current hybrid scheme. If seed pulse CEP comes from passive method, output pulse CEP cannot be controlled by active method.

#### 4. Conclusion

We developed a high efficiency, high energy, tunable phase-stabilized near-infrared femtosecond OPA at 3 kHz, which consists of a WLC stage and two non-collinear OPA stages with only one amplification medium (BBO). A hybrid control method stabilized the CEP of the tunable output pulses. The tunable output pulses were still CEP-stabilized by an actively CEP-stabilized seed and pump pulse. A single BBO crystal demonstrated a high efficiency two-stage NOPA. The highest conversion efficiency of 34% was achieved at 1350 nm in type II phase matching condition. The total tunable spectral range for the signal pulses was from 1100 nm to 1700 nm. The measured CEP jitter of the output pulses from the OPA was 117 mrad (rms) for an input jitter of 53 mrad. The maintenance of the stability of about 100 mrad over a longer period of time may require a slow feedback loop for suppressing possible slow drifts of CEP likely to occur over a period of tens of minutes or beyond. The single crystal configuration provides a simple and efficient way to produce tunable femtosecond pulses, leading to a compact system.

The laser light around 1350 nm has a 3 times larger ponderomotive potential than the 800 nm light. Hence the fs laser pulse around 1350 nm is capable to generate HOH in the water window region. The recent simulation study on two color scheme for the generation of isolated attosecond pulse [41] shows that the proper mixing of a weak fs light around 1300 nm with a strong 800 nm fs light can lead to the generation of isolated attosecond pulse using a rather long fs pulse.

The fs OPA laser around 1350 nm not only is used immediately to these two examples but also will find applications in various areas.

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