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Article

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Carrier-envelope phase passively stabilized near-infrared laser pulses from a dual-frequency pumped noncollinear optical parametric amplifier

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Abstract By inversing the signal and idler in a two-stage noncollinear optical parametric amplifier which is, respectively, pumped by the second harmonic and fundamental wave of femtosecond Ti:sapphire laser at repetition rate of 1 kHz, the carrier-envelope phase (CEP) passively stabilized pulses with a tunable wavelength from 1.1 to 1.6 μm are obtained with maximum energy of 95 μJ at 1.3 μm under the pump energy of 500 μJ. The CEP jitter of pulses is 108 mrad measured by an *f*-2*f* interferometer. This work demonstrates a new way to efficiently generate tunable near-infrared femtosecond laser pulses with self-stabilized CEP.

Keywords Noncollinear optical parametric amplifier · Femtosecond laser · Carrier-envelope phase · CEP jitter

1 Introduction

The carrier-envelope phase (CEP) of tunable femtosecond laser pulses plays a key role on realization of isolated attosecond pulse and ultrafast resolution applications of electronic transition in matters [1–3]. With the CEP stabilization, scientists are now able to directly access the electric field of an optical waveform, and it will pave a way to investigate the ultrafast phenomena in physics, chemistry, and biology sciences [4, 5]. Therefore, CEP-stabilized femtosecond laser pulse is very crucial to ultrafast sciences.

To stabilize the CEP of laser pulses, active and passive technologies have been developed. For the active scheme, CEP stabilization is basically realized by the active electronic control loops based on measurement of pulse to pulse phase slips of the oscillator [6–11]. Slow phase drifts in the amplifier can be characterized by the spectral interferometry based on *f*-2*f* principle and compensated by a second electronic feedback to control dispersion elements (prisms or gratings) in the laser system [7–11]. The whole locking procedure of active scheme is rather complicated, and the stability is very sensitive to external environmental disturbance. For the passive scheme, CEP stabilization is accomplished by difference frequency generation (DFG) [12–18] or optical parametric amplification (OPA) processes [14, 19–21]. The DFG is realized by mixing the wings of high frequency and low frequency in an ultra-broadband laser spectrum. Since both high- and low-frequency wings are from the same pulse, the CEP fluctuation will be canceled each other, and results in automatically phase stabilized. The idler is difference frequency between the pump and signal in OPA processes, if both of them are generated from the same source, the idler is also automatically CEP stabilized. Compared with the method of active CEP stabilization, the passive CEP stabilization is easier to realize, because it only depends on the synchronization of two separated frequency shifted pulses. The long-term phase stabilization for this kind of optical system can be expected.

Carrier-envelope phase passively stabilized laser pulses from DFG or OPA processes pumped by the fundamental wave of Ti:sapphire amplified laser have been widely

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researched [12–21]. Further, the CEP-stabilized idlers which are generated from the second harmonic of Ti:sapphire amplifier also have been reported in some groups [22–24], but further amplification for this kind of seed has not been realized. In this paper, we introduce a dual-frequency pumped laser system for generation of CEP-stabilized laser pulses by a two-stage NOPA. The idler with stable CEP is generated from the first NOPA stage (NOPA1) which is pumped by the second harmonic of Ti:sapphire laser, and then it is served as the seed in the second NOPA stage (NOPA2) pumped by the Ti:sapphire laser. The wavelength of the CEP stable amplified pulses can be tuned from 1.1 to 1.6 μm. The energy of amplified pulse is up to 95 μJ at 1.3 μm under the pump energy of 500 μJ at 800 nm from NOPA2. The CEP jitter is measured to be 108 mrad by a spectral interferometry based on *f*-2*f* principle. The scheme demonstrates an efficient way to generate tunable femtosecond laser pulses with self-stabilized CEP.

2 Experimental setup of two-stage NOPA

Figure 1 shows the experimental layout of our two-stage NOPA setup. A commercial Ti:sapphier multipass chirped-pulse amplification (CPA) laser (Femtolaser Inc.) is used as the pump source which provides laser pulses with energy of 700 μJ in 30 fs at repetition rate of 1 kHz, the central wavelength is 800 nm. The experimental setup mainly consists of three parts: white-light continuum (WLC) generation and two-stage NOPA amplifiers. The WLC is used as the seed (signal) for NOPA1 with the second harmonic of Ti:sapphire laser as the pump. The CEP stable idler pulses are generated from this stage. A 10-mm hollow fiber with a diameter of 250 μm is employed to compensate the spatial dispersion of idler laser beam from the NOPA1, and then the idler pulses are amplified in the NOPA2 pumped by the Ti:sapphire laser.

The laser beam from the pump source is collimated by a reverse beam-expander with the ratio of 2:1. The main beam with energy of 700 μJ from the pump source is divided into three parts by two beam splitters BS1 and BS2. A 50 μJ fraction of the pulses are focused into the lithium borate (LBO2) crystal by lens L5 for the second harmonic (SH) generation. The remaining part of fundamental frequency pulses without converting into SH is eliminated from the optical path by a Glan polarizer. The WLC which is served as the seed of NOPA1 is generated by focusing about 2 μJ SH pulses into the 2 mm CaF_2 plate based on the self-phase-modulation effect. The second harmonic for pumping NOPA1 is generated by focusing another 150 μJ fraction of the pulses passing through BS1 into LBO1. The energy of SH pulses were up to 10 μJ by optimization of the energy density of the fundamental frequency pulse on the LBO1. Then, the CEP-stabilized idlers can be obtained from NOPA1 due to the seed and pump are from the same source (second harmonic laser). The nonlinear crystal for the parametric process is β-barium borate (BBO) with thickness of 2 mm, which phase match angle is at $\theta = 26.7°$ for type I [o + o (idler)→e (pump)]. The non-collinear angle between the pump and seed (signal) is about 3° in this setup. In order to improve the parametric conversion efficiency and beam quality of NOPA2, a 10 mm hollow core fiber with a diameter of 250 μm is employed for compensation the spatial dispersion of idler pulses from NOPA1, and the energy coupling efficiency of this fiber is

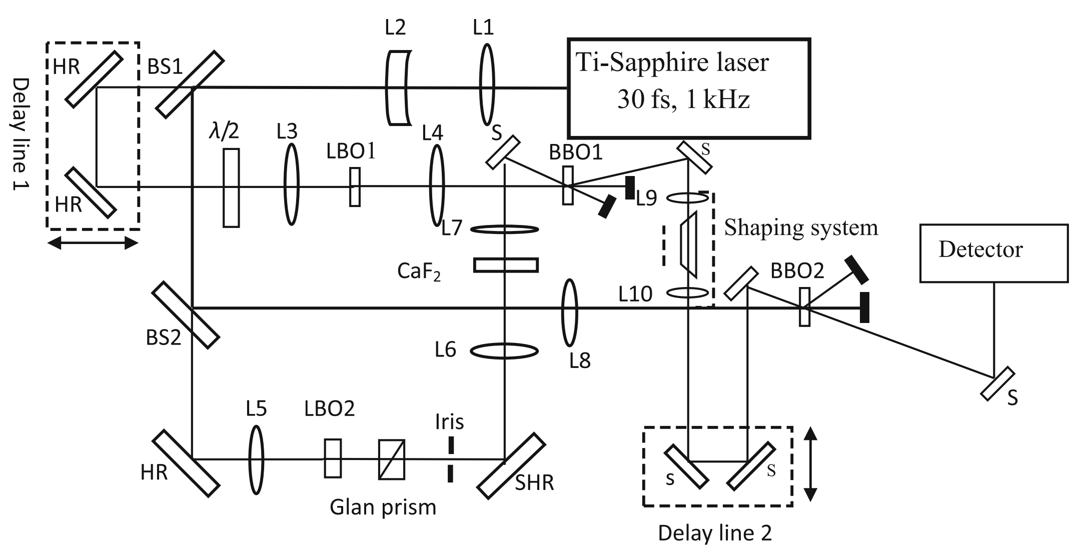

Fig. 1 Schematic of generation of passively CEP stable pulses based on two-stage NOPA. *L1–L10* lens, *HR* high reflector at 800 nm, *SHR* high reflector at 400 nm, *λ*/2 half-wave plate at 800 nm, *BS1*, *BS2* beam splitters, *S* silver mirror

55 %. The reshaped beam is injected into NOPA2 stage which is pumped by the fundamental frequency of the Ti:sapphire laser with energy of 500 μJ. Another BBO crystal with thickness of 2 mm and cut at $\theta = 20°$ to fit type I [o + o (idler)→e (pump)] phase matching is used in NOPA2. The noncollinear angle is about 3.2°. To avoid damaging the parametric crystal and generating superfluorescent, the beam diameter of the pump laser in the crystal is controlled to be about 1.5 mm, corresponding to the power intensity of 240 GW/cm^2.

3 Results and discussion

With optimization of the pump power density, finely temporal synchronization, and space overlap between the pump and signal in two NOPA stages, the pulse energy up to 95 μJ at the central wavelength of 1.3 μm is obtained. The central wavelength of generated pulses from the NOPA2 can be tuned from 1.1 to 1.6 μm by adjustment of the phase matching angle of BBO crystals, as shown in Fig. 2. The spectrum bandwidth is increased to the maximum at 1.6 μm because of a broad phase matching bandwidth at degeneracy for type I OPA.

In order to prove the CEP stability of the laser pulses from the NOPA2, we set up an *f*-2*f* interferometer [20, 25], as shown in Fig. 3. The white-light supercontinuum (WLSC) with an octave-spanning spectrum is generated by focusing a small part of the amplified signal from NOPA2 into a 1-mm-thickness sapphire plate. The light intensity is controlled by two irises and an attenuator. The half-wave plate is employed to change the polarization state of light pulse. The WLSC is tightly focused into a 0.5-mm-thick BBO crystal to double frequency, and both the fundamental frequency of the short wavelength wing and second harmonic of the long wavelength wing in WLSC are directed to a spectrometer after a Glan polarizer. The *f*-2*f* interferometric spectra are recorded with time interval of 100 s, as shown in Fig. 4a. Obvious fringe patterns with high visibility are kept the same at different recording time. According to the spectral interference fringes, the CEP jitter is demonstrated to be 108 mrad (RMS) with 50 ms

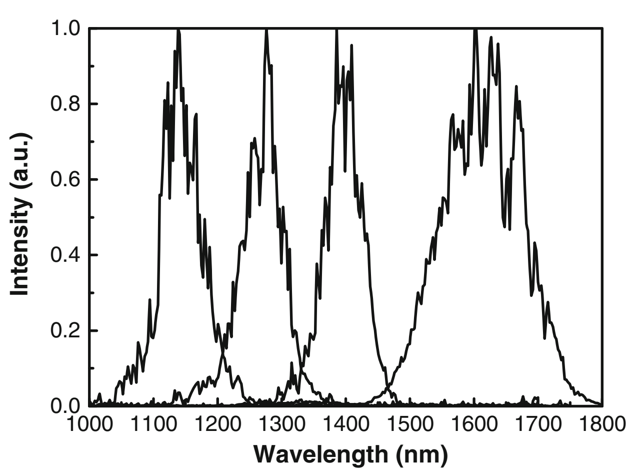

Fig. 2 Normalized tunable output spectra from the NOPA2

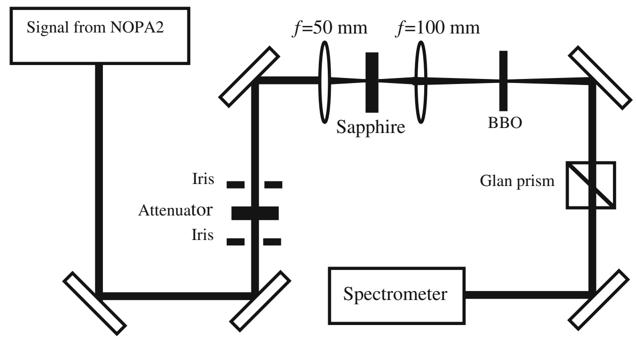

Fig. 3 Schematic of the *f*-2*f* spectral interferometer

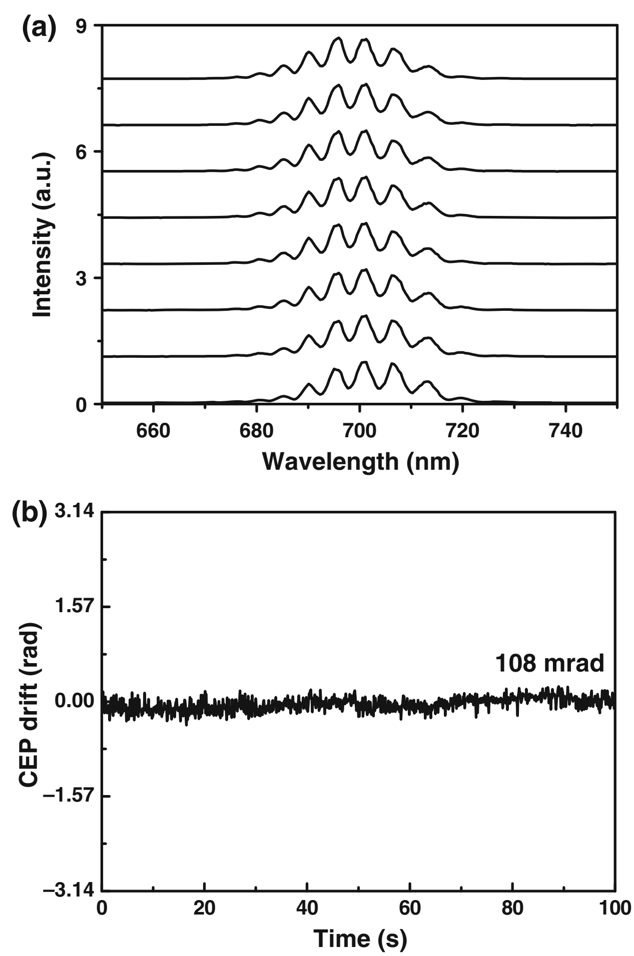

Fig. 4 **a** *f*-2*f* spectral interference fringes obtained by spectrometer with time interval of about 100 s, **b** the CEP deviation recorded with time, and the retrieved rms phase jitter is 108 mrad

integral time by a linear Fourier-transform spectral interferometry algorithm, as shown in Fig. 4b.

4 Conclusions

A CEP passively stabilized near-infrared laser from a dual-frequency pumped NOPA pumped by 400 and 800 nm femtosecond laser, respectively, is developed. The self-stable CEP laser pulses with central wavelength from 1.1 to 1.6 μm are demonstrated by inversing the signal and idler laser pulses. The CEP jitter is measured to be 108 mrad by an *f*-2*f* interferometer. A 10-mm hollow core fiber with the diameter of 250 μm is employed to compensate for the angular dispersion of the idler beam from the NOPA1 stage, and the final amplified pulses with energy of 95 μJ at 1.3 μm with good beam quality are obtained under pumped by the fundamental laser with energy of 500 μJ. The CEP-stabilized pulses will be further amplified to higher energy by increasing pump pulse energy, and the number of the amplification stages and a compressor will be employed to compensate the dispersion of pulses in future plan.

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