Spectral Shaping and Continuous Tuning of Multi-color Carrier-envelope Phase Locked Pulse

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Abstract: We have demonstrated to generate multi-color CEP-locked beams using the non-collinear optical parametric amplifier. Spatial filter in the spatially dispersed seed light has shaped spectrum and parabolic chirp was used to tune double color.
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1. Introduction

Carrier envelope phase (CEP) of the laser pulses are generally not locked in conventional laser systems. Meanwhile, CEP-locked laser pulse has various applications such as soft X-ray generation [1], frequency metrology [2], and control of diatomic molecule dissociation [3]. Therefore, various methods have been developed to lock the CEP. These methods can be roughly divided into two groups; active CEP-lock methods and passive CEP-lock methods. In active CEP-lock method [4], the laser spectrum is broadened over one octave using fiber. The high frequency component of the broadened spectrum was mixed with the double frequency of the low-frequency component to observe their interference (f-2f interferometer). The observed beat reflecting the change of CEP was used as feed-back signal to stabilize the CEP. Following that, we have developed another type of CEP-lock method called as passive CEP-lock method [5] using a non-collinear optical parametric amplifier (NOPA) [6]. The NOPA system was pumped with second harmonic (SH) of the Ti:sapphire laser pulse and seeded with the white-light continuum generated by the same SH. The CEP of the pump pulse randomly shifts its value pulse-to-pulse, but the amount of shift is equal to that of the seed pulse. Therefore, the idler pulse coming out from the NOPA is locked to a constant value not experiencing any frequency shift in pulse-to-pulse.

In the present work, we have developed and demonstrated two schemes to generate multi-color CEP-locked pulses. The CEPs of the pulses are self-stabilized by the NOPA. A seed pulse of the NOPA was spectral or temporally modified to generate multi-color CEP-locked pulse.

2. Experimental

The CEP-locked pulse with broadband spectrum was generated by a NOPA. As a source laser, we have used a Ti:sapphire regenerative amplifier (Legend-USP; Coherent Inc.) seeded with a Ti:sapphire laser oscillator (Micra-10; Coherent Inc.). The amplifier generates femtosecond pulses with 40fs (duration), 800 nm (central wavelength), 5 kHz (repetition rate), and 2.5 W (average power). The pulse from the regenerative amplifier was focused into a 1mm-thick β-barium borate (BBO) crystal to generate second harmonic (SH) with average power of 200 mW. The SH pulse was separated into two pulses by a beam sampler (BSF10-A; thorlabs).

A small portion of the SH pulse was reflected on the non-coated surface of the beam sampler and a lens focused the weak SH pulse into a calcium fluoride (CaF_2) plate to generate white light (WL) by self-phase modulation. The CaF_2 plate was pasted on a mechanical rotation stage and the plate was shaken continuously not to make a damage on the plate under irradiation of the SH beam. The WL pulse was used as a seed pulse of the NOPA. In the light path of the WL pulse, we have inserted a prism compressor, which consists of a pair of equilateral dispersive prism. The prism compressor had two functions in the present work. One is to adjust the chirp of the NOPA seed beam, resulting in wavelength tunability of the NOPA idler beam. Another function of the prism compressor is for arbitrary modulation in the NOPA seed spectrum, which could be performed inserting a spatial filter in the beam path of the seed beam spatially dispersed in the prism compressor.

A large portion of the SH pulse transmitted through the beam sampler. The intense SH beam stretched its pulse duration passing through a fused silica glass block with length of 40 mm, and used as a pump pulse of the NOPA. The long duration (~1ps) of the pump pulse avoids damage on the optical components and makes the NOPA output to be less sensitive to the timing drifts (between the pump pulse and the seed pulse). The tolerance to the timing drifts improves the power stability of the NOPA output.

3. Results and discussion

The duration of the SH pulse was shorter than that of the WL pulse. When the SH pulse overlaps with the center wavelength component of the WL pulse, the NOPA output has broadest band. Figure 1(a) shows the broadband idler spectrum obtained in the NOPA. Then, we have inserted the spatial filter in the light path of the seed beam, which modified the seed spectrum to have three peaks. Amplifying the three-peak seed spectrum in NOPA, the CEP-locked idler pulse also has three peaks in its spectrum (see Fig. 1(b)).

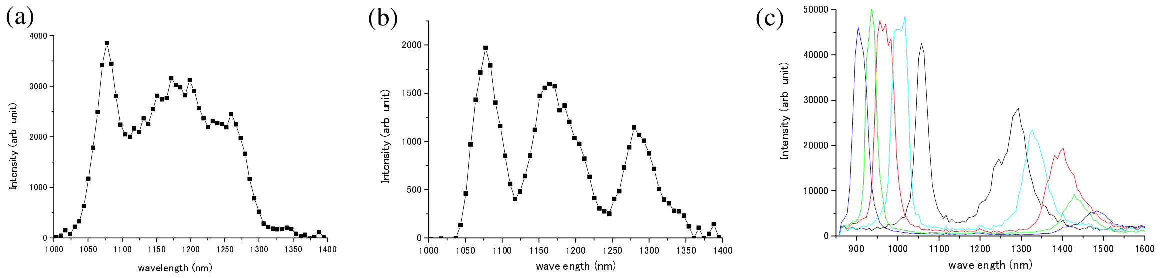

Fig. 1. Spectrum of the CEP-locked idler pulse (a) with broadband, (b) three colors, and (c) double color with color tunability.

The simulation results of group delay showed that the seed beam has the remaining parabolic chirp. When the SH pulse does not overlap with the center wavelength component of the WL pulse, the NOPA output will have two peaks in its spectrum. The wavelengths of the two peaks can be tuned by adjusting the delay between the SH pulse and the WL pulse. To adjust the delay between the SH pulse and the WL pulse, a corner reflector was inserted in the light path of the SH pulse. The position of the corner reflector was scanned by manipulating a micrometer of a manual positioning stage set under the corner reflector. Figure 1(c) shows the idler spectrum observed changing the optical delay between the SH pulse and the WL pulse at 40 μm step. The result shows that we could obtain two color CEP-locked pulse with wavelength tunability.

4. Summary

Focusing the SH pulse into a CaF_2 plate, the WL pulse was generated to be used as the seed pulse of NOPA, which is also pumped by the SH pulse. The WL seed pulse and the SH pump pulse share the same instability of CEP. The idler pulse of NOPA was generated by difference frequency generation between the SH pump pulse and the WL seed pulse, therefore the idler pulse has no instability in its CEP cancelling out the CEP instability. We have demonstrated two schemes to generate multi-color CEP-locked pulse. In the first scheme, we have modified the seed spectrum inserting a prism compressor and a spatial filter in the light path of the seed beam. The three color seed beam was amplified in the NOPA to obtain the three color idler beam whose CEP is self-stabilized. In the second scheme, we have adjusted the optical delay between the SH pump pulse and the WL seed pulse to obtain two color CEP-locked idler pulse whose wavelength is tunable. The two color amplification of the seed (and idler) beam was caused by the high order chirp introduced by the prism compressor in the light path of the WL seed beam.

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