Temporal Characterization of Front-End for Yb-Based High-Energy Optical Waveform Synthesizers

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Abstract: We demonstrate temporal characterization of the front-end for an Yb-based, passively CEP-stable, two-octave-wide, two-channel optical parametric synthesizer driven by slightly sub-picosecond pump pulses from a multi-mJ regenerative amplifier at 1 kHz.

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High-harmonic generation (HHG) is an established powerful method, which allows characterization of atomic or interatomic transitions below the femtosecond time scale in the extreme ultraviolet (XUV) and soft X-ray spectral regions. However, HHG is a very inefficient process to generate isolated attosecond pulses. Coherent optical pulse synthesis of high-energy, few-cycle pulses is one of the most promising methods to efficiently generate isolated attosecond pulses because of the flexibility in spectral shaping and scalability in spectral bandwidth as well as energy [1-4]. Since the HHG process is driven by the electric field $E(t)$ of an optical pulse, control of the carrier-envelope phase (CEP) is crucial. The CEP can be controlled either actively [2], requiring several feedback loops increasing the system's complexity, or passively, using the difference-frequency process [3-5].

Previously, we demonstrated passively CEP-stabilized synthesizers pumped by Ti:Sapphire laser technology [3,4], and we have been pursuing average-power scaling with Yb-based pump technology [6, 7]. In this particular study, we demonstrate the temporal characterization of a two-channel parametric synthesizer at the μJ energy level, which will serve as the seed source for a mJ-level pulse synthesizer. The system comprises two-octave, passively CEP-stable, two-channel optical parametric amplifiers (OPAs) driven by sub-picosecond pulses [8] from an Yb-based multi-mJ regenerative amplifier. The OPAs are seeded by a passively CEP-stable front-end based on white-light supercontinuum generation in bulk [9].

Fig. 1 shows the layout of the dual-channel OPA system driven by an Yb:KYW regenerative amplifier. The compressed output of the Yb:KYW regenerative amplifier delivering 4.2-mJ, 615-fs long pulses [3] is split between a front-end generating nJ-level, CEP-stable pulses with spectrum extending from the visible up to the Mid-IR, and the pumping of two 2-stage OPA channels in the Near and Mid-IR spectral regions. The CEP-stable front-end comprises 3 steps: a first white-light stage broadens the spectrum of the regenerative amplifier; 2 consecutive OPA stages amplify a narrow-band spectral region to the μJ level in the Mid-IR; the second harmonic of the resulting CEP-stable idler generates white-light in YAG, which is the seed of the following OPAs [3,4].

Fig. 1. Layout of the dual-channel OPA system driven by an Yb:KYW regenerative amplifier: the signal is generated in the CEP-stable white-light based front-end, and spectra after amplification and compression stages are shown.

The Near-IR non-collinear OPA (NOPA) stages are pumped by the second harmonic of the regenerative amplifier at 515 nm with 5.7 μJ (NOPA1) and 132 μJ (NOPA2) and resulted in an output energy of 24 μJ at the end of the second stage without any superfluorescence. The amplified spectrum extends 640 and 960 nm supporting 7.7-

fs (FWHM) transform-limited pulses. The residual dispersion of the amplified pulses is compensated by employing double-chirped mirror (DCM) pairs designed for octave-spanning Ti:Sapphire oscillators.

The Mid-IR degenerate OPA (DOPA) stages are pumped at 1030 nm with 95 μJ (DOPA1), 35 μJ (DOPA2), 570 μJ (DOPA3) pulse energies. For precision dispersion control, an Acousto-Optic Programmable Dispersive Filter (AOPDF) is implemented between the first and second stages accompanied by a 2-mm YAG plate, which provides negative dispersion. The second DOPA stage is employed to compensate for the losses due to AOPDF. At the end of the third-stage DOPA, the pulses are amplified to 16 μJ . The spectrum is extending the range from 1840-2460 nm, and supports 28.4-fs pulses. Then the pulses are compressed inside two anti-reflection-coated ZnSe wedges with propagation distance of 1.5 mm.

Fig. 2 shows the temporal characterization of the pulses in the Near-IR (top row) and Mid-IR (bottom row) channels by using the second-harmonic FROG technique. In the Near-IR, the compression is achieved down to 12.1 fs (full width at half maximum, FWHM) by using 5 DCM pairs, while the transform-limited pulse duration is 7.7 fs. The corresponding FROG retrieval error is 0.81 %. After compression, the pulse energy is reduced from 24 to 22 μJ due to losses of the imaging metallic optics. The spectral phase in the short wavelength region is not compensated because of the limited-capability of the DCMs in this region. The compression can be further improved by using either custom-designed DCMs or a pulse shaper in the Near-IR. On the other hand, the AOPDF adaptively controls the dispersion of the Mid-IR channel. As can be seen from the SHG-FROG results (Fig. 2 second row), the spectral phase is almost constant over the full spectral range, which results in a pulse duration of 31.1 fs, close to its transform-limit (28.4 fs). The corresponding FROG error is 0.16 %.

Fig. 2. SHG-FROG characterization of the OPA outputs from the two channels. Near-IR NOPA (top row) and Mid-IR channels (bottom) are shown. (a) Measured and (b) retrieved FROG traces. (c) Measured spectrum, retrieved spectral intensity and phase. (d) Retrieved temporal intensity and phase profiles. The retrieved FWHM pulse durations are indicated.

In summary, we demonstrate the temporal characterization of a passively CEP-stable two-octave-wide pulsed light source with μJ energy levels. The NIR channel is compressed down to 12.1 fs, while the IR channel is compressed to 31.2 fs. Our current aim is to scale up the energy with further OPA stages employing cryogenically cooled high-energy Yb-based pump amplifiers and combine them coherently to obtain sub-cycle pulses. This is an ideal seed source for a two-octave-wide optical waveform synthesizer with high-energy and high repetition rate.

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