CEP-stable, few-cycle, kHz OPCPAs for attosecond science: Energy scaling and coherent sub-cycle pulse synthesis

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High-energy, carrier-envelope phase (CEP)-stable, few-cycle optical pulses have been a major driving source for producing isolated attosecond pulses via high-order harmonic generation (HHG). Besides the Ti:sapphire chirped-pulse amplification (CPA) technology with external pulse compression technique, recently, ultrabroadband optical parametric chirped-pulse amplification (OPCPA) has been regarded as a very promising technology for next-generation attosecond science because of several unique features, such as wavelength coverage from the visible to the mid-infrared, energy scalability to well above the mJ level while maintaining few-cycle pulse durations, and low CEP drift during the amplification. Especially, mid-IR few-cycle OPCPA [1] can greatly extend the cut-off energy of HHG, enabling attosecond science at high photon energy approaching keV [2].

In this paper, we present 1) the energy scaling of a CEP-stable, few-cycle, kHz OPCPA at 2.1 μm using a high-energy, ps, cryogenic Yb:YAG CPA laser [3] and 2) the coherent synthesis of its pulse with a CEP-stable, few-cycle, 800-nm pulse for sub-cycle pulse generation [4]. Fig. 1 shows the schematic of a 2.1- μm OPCPA system with two optically synchronized pump lasers, Nd:YLF (1st and 2nd stages) and Yb:YAG (3rd stage) lasers. The seed is generated by intra-pulse difference-frequency generation from an octave-spanning Ti:sapphire oscillator and is thus passively CEP stabilized. The CEP-stable, 2.1- μm pulse was amplified to 0.8 mJ with a bandwidth of >470 nm, supporting 3.5-cycle duration. Compression was achieved using Brewster-cut Suprasil300 glass. Further OPCPA optimization and HHG experiments will be discussed. Secondly, to push the pulse duration down to the single-cycle limit by coherent pulse synthesis, we developed a CEP-stable, 3-cycle OPCPA at 800 nm pumped by a

Fig. 1 Few-cycle, kHz, 2.1- μm OPCPA pumped by optically synchronized Nd:YLF and cryogenic Yb:YAG CPA lasers (YDFA, Yb-doped fiber amplifier; CFBG/CVBG, chirped fiber/volume Bragg grating; MLD, multi-layer dielectric; RGA, regenerative amplifier).

frequency-doubled Nd:YLF laser. The compressed output from the second stage of the 2.1- μm OPCPA was combined with the 800-nm pulse. A balanced cross-correlator with a feedback loop locked the timing between two pulses with a jitter of ~ 250 as. The synthesized pulse duration of ~ 0.6 cycle was measured using two-dimensional spectral shearing interferometry (2DSI) and the pulse energy was 15 μJ , scalable to $\sim \text{mJ}$ level using the cryogenic Yb:YAG pump laser. Simulations confirm the feasibility of direct isolated attosecond pulse generation using this waveform.

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