Above-Millijoule Optical Waveforms Compressible to Sub-fs Using Induced-Phase Modulation in a Neon-Filled Hollow-Core Fiber

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Abstract: We demonstrate 1.7-mJ optical waveforms based on induced-phase modulation for generating sub-femtosecond optical pulses. Using custom-designed double-chirped mirrors and a spatial light modulator, such optical waveforms will become a versatile tool for strong-field attoscience.

Coherent optical waveform synthesis aims to generate intense, custom-tailored, sub-cycle optical waveforms, which is currently one of the most intriguing and promising frontiers of attoscience and strong-field physics. Up to now, coherent waveform synthesis based on self-phase modulation (SPM) in a neon-filled hollow-core fiber (HCF) compressor allowed the generation of sub-cycle ~300-µJ optical pulses [1]. For pursuing the synthesis of the shortest possible pulses within this scheme, the total output energy of this multi-channel synthesizer is limited to a few tens of µJs mainly by the UV channel containing the smallest pulse energy [1], which might be not sufficient for many interesting applications in attoscience. A potential solution out of this dilemma is the application of induced-phase modulation (IPM) [2] based on the interaction between two (or more) co-propagating optical pulses of different color and relatively long pulse duration in a gas-filled HCF. The IPM technique offers control over the spectral shape by adjusting the relative intensity ratio and the relative delay between the input pulses and allows a more efficient generation of ultra-broadband optical pulses than those produced solely by SPM. Such an IPM-based synthesizer is expected to greatly relieve the energy-scaling bottleneck in the UV region [3], and the enhanced spectral broadening of the UV region is particularly appealing for the realization of ultrahigh HHG conversion efficiencies in bright tabletop high-harmonic sources.

By employing the advantages of IPM, we have demonstrated an isolated 1.3-cycle pulse with 2.6-fs duration and 3.6- µJ energy centered at 600 nm [2]. Later, much broader spectra (270–1000 nm) with several hundred µJ have been generated, supporting 1.5-fs transform-limited (TL) pulses [2]. Most importantly, attosecond optical waveforms with above-mJ energy would have a tremendous impact for applications in attoscience and strong-field physics. In this work, we demonstrate for the first time an above-mJ IPM waveform synthesizer driven by a carrier-envelope phase (CEP) stabilized chirped-pulse amplification (CPA) system. Using a neon-filled fused-silica HCF, we achieved a 1.72-mJ CEP-locked supercontinuum spanning the range 340–950 nm, which is straightforwardly compressible to terawatt attosecond optical waveforms.

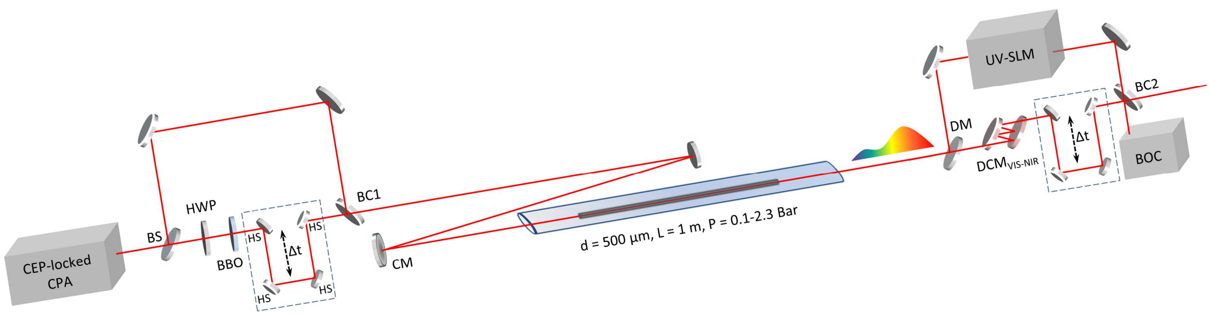

Fig. 1. Sub-femtosecond IPM-based optical waveform synthesizer: BS, beam splitter; BBO, β-barium borate crystal; HWP, half-wave plate; HS, harmonic separator; BC, beam combiner; CM, concave mirror; DM, dichroic mirror; DCM, double-chirped mirror; SLM, spatial-light modulator; BOC, balanced optical cross-correlator.

The experimental setup is shown in Fig. 1. The output beam of an 800-nm, 30-fs, 5.5-mJ CEP-stabilized Ti:sapphire CPA system with a 3 kHz repetition rate was divided into two beams by a beam splitter (BS) with a splitting ratio of 55:45 (reflectance/transmittance). The reflected pulses were used as fundamental pulses. The transmitted pulses passed through a half-wave plate (HWP), followed by a 0.5-mm-thick type-I β-barium borate (BBO) crystal to generate the second-harmonic (2ω) pulses at 400 nm with the same polarization as the reflected pulses at 800 nm. Two pairs of harmonic separators (HSs) were used to filter out the residual fundamental pulses from the second-harmonic pulses, as well as to adjust the time delay Δt for optimum IPM. The ω and 2ω pulses were recombined using a dichroic mirror and reflected by a concave silver mirror with a focal length f=1900 mm, which focused the combined beam into a fused-silica HCF (length L=1150 mm, diameter d=500 µm). The fiber was placed in the middle of a 400-cm-long glass tube sealed at the two ends with 3-mm-thick CaF_2 windows at Brewster angle. To obtain the broadest IPM output spectrum, a fundamental pulse with 2.3-mJ energy and a second-harmonic pulse with 420-µJ energy were focused and injected into the HCF filled with neonat the pressure of 2.3-bar. Figure 2(a) shows a 1.72-mJ IPM output spectrum (covering 365-930 nm, measured at 1% of the peak intensity) supporting 0.9-fs (TL) pulses (Fig. 2). After splitting this broadband light source into two different wavelength channels (UV, VIS-NIR) using a broadband dichroic mirror (DM), we plan to compress the different spectral regions using custom-designed double-chirped mirrors ($DCM_{VIS\text{-}NIR}$) and a UV spatial-light modulator (SLM) [4]. Finally, we will recombine the two channels by another broadband dichroic mirror. We also need to tightly lock the relative timing of the two pulses using a feedback loop employing a balanced optical cross-correlator (BOC), that can achieve sub-cycle synchronization with <30-as (rms) timing jitter [5]. To demonstrate the feasibility of compressing this broadband spectrum, we present for the first time SHG-FROG pulse-characterization results (Fig. 3) of the NIR channel. The dispersion compensation scheme includes $DCM_{VIS\text{-}NIR}$ pairs (covering 660-1000 nm), plates and wedges (SiO2) for dispersion fine-tuning, and the CaF_2 window of our future experiment's vacuum chamber. The SHG-FROG measured and retrieved temporal intensity and phase profiles as well as the TL intensity profile are presented in fig. 3. The compressed 9.3-fs pulses are very close to 8-fs Fourier limited.

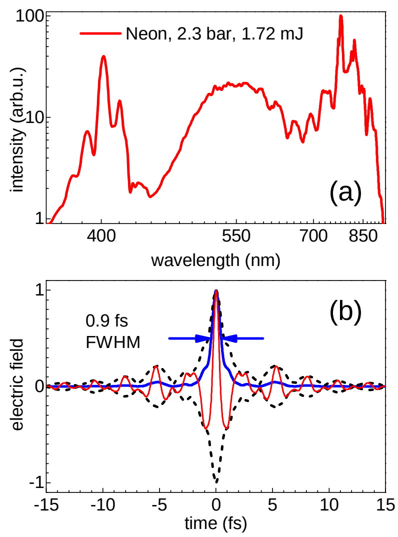

Fig. 2. (a) Supercontinuum created by IPM, (b) the corresponding TL pulse (Red: electric field *E(t)*; dashed: filed envelope; blue: intensity *I(t)*).

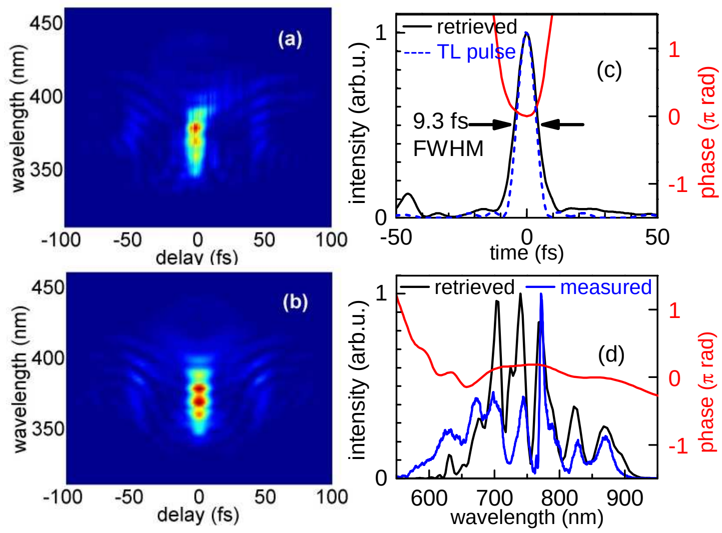

Fig. 3. SHG-FROG characterization of the NIR channel: (a) Measured and (b) retrieved FROG traces. (c) FROG retrieved temporal intensity and phase profiles as well as TL intensity profile. (d) Measured spectrum, FROG retrieved spectral intensity and phase.

In conclusion, we have discussed the technological challenges of an above-mJ IPM-based optical waveform synthesizer and presented first spectro-temporal characterization results of the NIR channel. By employing custom-designed DCMs and a UV-SLM in the near future, we foresee that this high-energy sub-fs synthesizer will become a versatile tool for nonlinear attosecond optics experiments [6].

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