

Towards parametric synthesis of millijoule-level two-octave-wide optical waveforms for strong-field experiments

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Abstract: We discuss a carrier-envelope phase-stable, 3-channel parametric synthesizer for creating a 2-octave-wide spectrum (0.5-2.2 μ m). The synthesizer output is straightforwardly scalable to the millijoule level with \sim 1.8-fs pulse duration, rendering it a versatile tool for attosecond science.

The coherent synthesis of custom-tailored, intense, few-cycle optical waveforms is currently one of the most intriguing and promising frontiers of attosecond science and strong-field physics, opening up unprecedented prospects, e.g., for precision control of strong-field interactions in atoms, molecules and solids, for the generation of intense isolated attosecond pulses, and for attosecond pump-probe spectroscopy employing ultrashort pulses in the VIS/IR and XUV/soft-X-ray regions. The key ingredients of coherent pulse synthesis are (i) the creation of an ultrabroad spectrum, (ii) extremely precise dispersion control over the whole bandwidth, (iii) sub-cycle timing synchronization as well as tight stabilization of the relative phases between the different pulses, and (iv) carrier-envelope phase (CEP) stability required for creating reproducible electric-field transients.

Recently, coherent pulse synthesis based on supercontinuum generation in a neon-filled hollow-core fiber compressor allowed the generation of sub-cycle \sim 300- μ J optical pulses (\sim 250 μ J energy in the NIR channel, \sim 35 μ J in the VIS, and \sim 15 μ J in the VIS-UV).¹ However, the energy throughput of such hollow-core fiber compressors is limited by ionization losses in the gas medium, thus preventing further energy upscaling to the (multi-)mJ level, which is required for many interesting applications in attosecond science. In contrast, parametric synthesizers²⁻⁵ do not face an energy-scaling bottleneck, and spectral extension into the MIR region is particularly appealing for the realization of bright coherent tabletop high-harmonic sources in the water-window and keV X-ray region.⁶

In our earlier works, we already demonstrated coherent pulse synthesis between ultrabroadband 870-nm and 2.15- μ m pulses based on optical parametric chirped-pulse amplification (OPCPA) resulting in a 15- μ J sub-cycle waveform,² and also between two optical parametric amplifiers (OPAs) with 1-2 μ J energy each.³ Here, we present our ongoing development of a novel 3-channel parametric synthesizer for creating a 2-octave-wide spectrum, which can straightforwardly be upscaled in energy to the millijoule-level with \sim 1.8-fs FWHM duration.

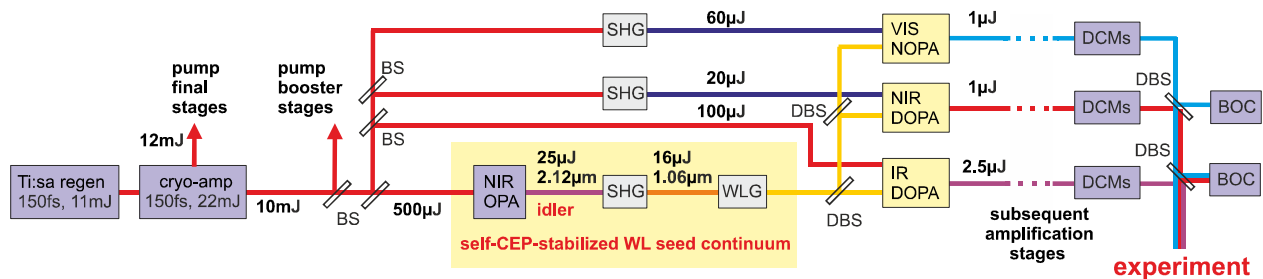


Fig. 1. Scheme of the 2-octave-wide parametric synthesizer. BS, beam splitter; SHG, second-harmonic generation; WLG, white-light generation; DBS, dichroic beam splitter; NOPA, noncollinear OPA; DOPA, degenerate OPA; DCMs, double-chirped mirrors; BOC, balanced optical cross-correlator. Energy upscaling in subsequent amplification stages is only indicated for the sake of clarity.

The scheme of the parametric synthesizer is depicted in Fig. 1. Starting point is a cryogenically cooled 1-kHz Ti:sapphire chirped-pulse amplification system delivering compressed 150-fs \sim 10-mJ 0.8- μ m pulses from its main output port, and \sim 12-mJ pulses from its second output port (that eventually will be used for pumping the final booster OPAs). A CEP-stable seed continuum⁵ covering the bandwidth of all three OPAs (0.5-2.2 μ m) is obtained by white-light generation in a 3-mm-long YAG crystal from the second harmonic (1.06 μ m) of the passively CEP-stable idler (2.12 μ m) of a NIR OPA pumped by the fundamental pulses. Using custom-designed dichroic beam splitters, the CEP-stable white-light continuum is diverted to seed the VIS noncollinear OPA (NOPA) as well as the NIR and IR degenerate OPAs (DOPAs). These OPAs are pumped by the 400-nm second-harmonic and 800-nm fundamental pulses, respectively, as shown in Fig. 1. After parametric amplification, the three OPA outputs can individually be recompressed using custom-tailored double-chirped mirrors (DCMs). Finally, in order to synthesize a coherent ultrashort pulse from these three OPAs, the relative timing of the pulses will be tightly locked using balanced optical cross-correlators (BOCs), which have been demonstrated to achieve sub-cycle synchronization with $<$ 30-as RMS timing jitter.^{2,3}

Fig. 2(a) shows the measured output spectra from the first amplification stages operating in parallel. All three OPAs employ 1-mm-thick type-I BBO crystals (the phase-matching angle θ is 31°, 29°, and 20.1° for the VIS NOPA, NIR DOPA and IR DOPA, respectively). The VIS NOPA and NIR DOPA continuously cover the region from 490 nm to 1000 nm. The IR DOPA yields a spectrum from 1.1 μ m to 2.2 μ m, the peak centered at 1.06 μ m stems from the residual idler-SHG (creating the white-light seed) and is not amplified in the IR DOPA. The transform-limited FWHM pulse duration from the synthesis of these three spectra is \sim 1.8 fs [see Fig. 2(b)].

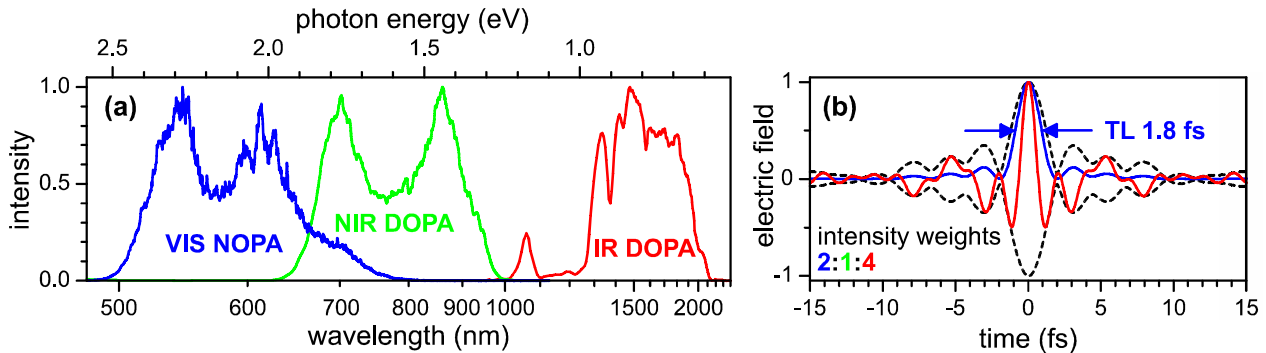


Fig. 2. (a) Output spectra from the first OPA stages. The energies of the amplified signal pulses are 1 μ J for the VIS NOPA and NIR DOPA, and 2.5 μ J for the IR DOPA. (b) The transform-limited (TL) pulse synthesized from the weighted spectra in (a) corresponds to a \sim 1.8-fs FWHM pulse duration. The red curve is the electric field $E(t)$, the dashed curves indicate the field envelope, the temporal intensity profile $I(t)$ is the blue trace.

Our current work aims to scale up the energies (by two subsequent amplification stages) to \sim 0.5 mJ for the VIS NOPA/NIR DOPA and \sim 2 mJ for the IR DOPA using the remaining 8.5 mJ of pump from the main and 12 mJ from the second output. The enabling technology for the final pulse compression to a \sim 1.8-fs duration and successful beam recombining (avoiding B -integral issues) are state-of-the-art DCM pairs with ultralow residual ripple in the resulting total group-delay dispersion over the full bandwidth (0.5-2.2 μ m), which are at present in the process of being fabricated. Temporal characterization of the synthesized two-octave-spanning optical waveforms will be performed by two-dimensional spectral shearing interferometry (2DSI).^{2,3}

We foresee that our 3-channel synthesizer, when scaled in energy to the millijoule level, will become a versatile tool for controlling strong-field interactions in atoms, molecules and solids and for attosecond pump-probe spectroscopy employing ultrashort pulses in the VIS/IR and XUV/soft-X-ray regions.

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