High-Energy Optical Waveform Synthesis

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There is a growing number of strong-field processes that greatly benefit from the availability of single-cycle to sub-cycle optical pulses, especially the generation of intense isolated attosecond XUV pulses [1], relativistic laser-plasma interactions and laser-driven electron acceleration [2], in-vacuum acceleration [3], launching valence-electron wavepacket dynamics in atoms and molecules [4], and control of sub-cycle electron transport in solids [5], which all can be summarized as examples of *"Waveform Nonlinear Optics"*.

Depending on the requirements (energy, spectral bandwidth, pulse duration, repetition rate etc.) of the targeted application, different technological approaches have recently been pursued to generate such waveforms [6]. Here, we focus on a parallel high energy optical waveform synthesizer approach pioneered at CFEL, Hamburg, which is a multi-mJ, more than 2-octave wide optical waveform synthesizer covering the wavelength range from 0.5 - 2.5 μm using parametric amplification [9]. Key to energy-scalable synthesis are (i) broadband carrier-envelope phase (CEP) stable continuum generation, that can serve as a seed for the synthesizer; (ii) a powerful and energetic fs or ps-pump laser technology for powering the multi-channel OPAs or OPCPAs that amplify the seed radiation to the desired energy level; (iii) two-octave spanning dichroic dispersion compensating mirrors to split and recombine spectral ranges without introducing phase distortions that cannot be compensated for [13]; (iv) appropriate nonlinear crystals that support broadband optical parametric amplification and (v) a device to stabilize the relative timing and phase of the individually amplified wavelength channels, i.e., to execute the waveform synthesis. Figure 1 shows the scheme of a >2-octave-wide 3-channel parametric synthesizer, that can be either powered by 1-μm lasers using fundamental second and third harmonic or the fundamental and second harmonic of a Ti:sapphire laser. Meanwhile, we have built all OPA stages and performed jitter measurements between two of the channels indicating a passive stability between different channels of less than 5 fs in 1 second. This stability is good enough to implement feedback loops to ensure permanent waveform synthesis to a level better than one tenth of an optical cycle [7,8]. A detailed characterization of all subsystems and the currently achieved synthesized waveforms will be presented.

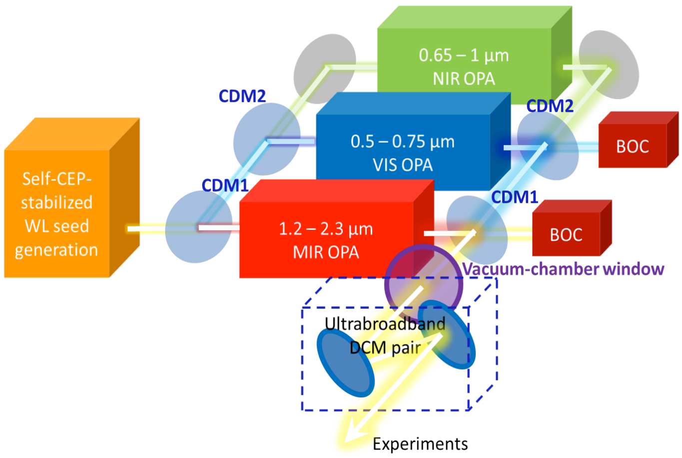

Fig. 1. Scheme of a >2-octave-wide 3-channel parametric waveform synthesizer. CEP, carrier-envelope phase; WL, white-light; CDM, chirped dichroic mirror; OPA, optical parametric amplifier; DCM, double-chirped mirror; BOC, balanced optical cross-correlator. [13]

References:

[1] E. J. Takahashi *et al.*, Nat. Commun. **4**:2691 (2013); E. J. Takahashi *et al.*, Phys. Rev. Lett. **104**, 233901 (2010).
[2] L. Veisz *et al.*, CLEO Pacific Rim 2013, paper TuD2-3.
[3] L.-J. Wong *et al.*, Opt. Lett. **36**, 957 (2011).
[4] A. Wirth *et al.*, Science **334**, 195 (2011). Also see: M. T. Hassan *et al.*, Rev. Sci. Instrum. **83**, 111301 (2012); T. T. Luu *et al.*, QELS 2013, paper QF1C.6. S. Fang et al., HILAS 2014, paper HW1C.2; S. Fang et al., Ultrafast Phenomena 2014, paper 09.Wed.P3.60.
[5] O. D. Mücke, Phys. Rev. B **84**, 081202(R) (2011); S. Ghimire *et al.*, Nature Phys. **7**, 138 (2011); A. Schiffrin *et al.*, Nature **493**, 70 (2013);
[6] C. Manzoni *et al.* Laser & Photonics Rev. submitted (2014).
[7] S.-W. Huang *et al.*, Nature Photonics **5**, 475 (2011); S.-W. Huang *et al.*, J. Phys. B **45**, 074009 (2012).
[8] C. Manzoni *et al.*, Opt. Lett. **37**, 1880 (2012).