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SPRINGER SERIES IN CHEMICAL PHYSICS 92

Ultrafast Phenomena XVI

Springer

Corkum · De Silvestri
Ultrafast

Part X: Frequency Combs and Waveform Synthesis

Multimillijoule Optically Synchronized and Carrier-Envelope-Phase-Stable Chirped Parametric Amplification at 1.5 µm

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Abstract. Efficient infrared 35-THz-wide parametric amplification at 1.5 µm with the energy of ~10 mJ is obtained in a 4-stage OPCPA using a combination of a 1030-nm 200-fs Yb- and a 1064-nm 60-ps Nd amplifier seeded with a common Yb oscillator.

Optical Parametric Chirped Pulse Amplification (OPCPA) [1] has attracted a lot of attention as a promising route toward intensity scaling of few-cycle laser pulses. Intense phase-stable few-cycle laser pulses have numerous intriguing applications in attosecond science and high-field science including attosecond XUV/soft-X-ray pulse generation by high-harmonic generation (HHG), tomographic imaging of molecular orbitals, and laser-induced electron diffraction. A major challenge for using HHG in studies of time-resolved tomography of molecular dissociative states is the low ionization potential I_p of excited molecular states. The resulting competition between state depletion and HHG prevents generation of broad HHG spectra necessary for tomographic reconstruction. One solution are laser sources with high ponderomotive energy $U_p \propto \lambda^2 I$ at moderate intensity level, i.e., infrared phase-stable few-cycle high-power laser systems. High-U_p-sources [2,3] also open the door to experimental investigations of the λ-scaling laws of strong-field physics (Keldysh parameter $\propto\lambda^{-1}$, electron energies $\propto\lambda^2$, HHG cutoff $\propto\lambda^2$, HHG efficiency $\propto\lambda^{-5.5}$, minimum attosecond pulse duration $\propto\lambda^{-1/2}$ [4]), and they would benefit laser-induced electron diffraction because of the shorter de Broglie electron wavelength and consequently higher spatial resolution [5]. The main objective of our work is to generate IR pulses with ~40-fs duration that fully satisfy the requirements for external spectral broadening in gas [6]. In addition, with an IR pulse we expect to surpass the energy limitation (4-5 mJ at 0.8 µm) for gas broadening schemes because the critical power of self-focusing also scales as λ^2.

Using mJ pulses from Ti:sapphire amplifiers at 0.8 µm, coherent X-rays in the keV photon energy range were generated by HHG in helium [7]. A technological problem hindering further scaling of the pulse energy beyond several mJ is gas ionization in the gas-filled hollow-fiber compressors required to achieve few-cycle pulse duration at mJ pulse energies. More fundamentally, ionization in helium saturates when the intensity of a few-cycle pulse at 0.8 µm exceeds ~1 PW/cm^2, thus the HHG cutoff and photon flux is limited by ground-state depletion in helium in these experiments.

Here, we report on the development of a multi-mJ all-optically synchronized and phase-stable OPCPA at 1.5 µm (see Fig. 1). As opposed to our OPCPA systems developed previously, in this work we modify our approach: (1) with the advent of a

mature 200-fs Yb MOPA system it became possible to abandon the Ti:sapphire front-end; (2) we avoid working close to the signal-idler wavelength degeneracy and reduce the quantum defect for the signal wave; (3) we employ (nearly) collinear Type II phase matching that, as opposed to Type I, supports a much narrower bandwidth but is free of parasitic self-diffraction. Following the pioneering work of Miller and coworkers [8], we employ Type II KTP/KTA (1030/1064 nm pump, ~1500 nm signal, ~3500 nm idler) because these crystals are transparent for the mid-IR idler wavelength and exhibit a relatively broad bandwidth around 1500 nm. The repetition rate of the Yb:KGW DPSS MOPA (Pharos, Light Conversion, Ltd.), tunable in the range of 1–100 kHz, was set at 10 kHz as a 500-th harmonic of the flash-lamp pumped Nd:YAG amplifier (Ekspla Ltd.) operating at 20 Hz. In our scheme (Fig. 1), both Yb and Nd RA are simultaneously seeded from a single master oscillator that has a modest FWHM bandwidth of 30 nm. To seed the Nd RA, we pick up the 0th-order diffraction beam behind a transmission grating in the pulse stretcher.

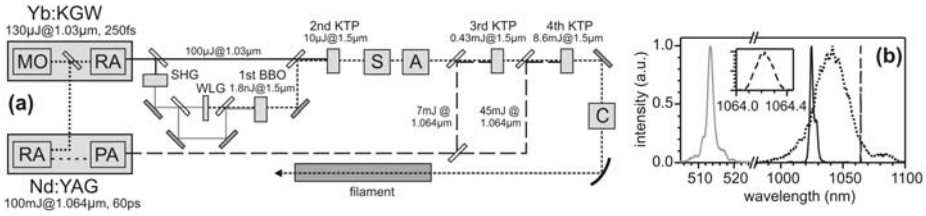

Fig. 1. (a) Scheme of the IR OPCPA setup. MO, master oscillator; RA, regenerative amplifier; PA, double-pass post amplifier; S/C grating-based stretcher/compressor; A, acousto-optic programmable dispersive filter (DAZZLER); WLG, white-light generator in a 4-mm-thick sapphire plate; the CEP-stable idler wave from stage 1 becomes the signal wave in stage 2. Stage 1 (BBO, Type I) is pumped at 515 nm, stage 2 (KTP, Type II) at 1030 nm, stages 3 and 4 (KTP, Type II) at 1064 nm. (b) Spectra of Kerr-lens mode-locked Yb:KGW oscillator (dotted), Yb:KGW RA (solid), SHG of Yb:KGW (grey). The Nd:YAG RA (dashed) contains an intracavity 2-mm-thick etalon to narrow the ps amplifier bandwidth.

The output of the Yb:KGW CPA system is used to pump the first two OPA stages. The frequency-doubled output at 515 nm is used to generate white light continuum in sapphire and as a pump of the 1st stage (collinear Type I BBO). This configuration produces a carrier-envelope phase (CEP) stable idler [9] at 1.5 μm that we further use as seed (signal wave) in the subsequent OPA stages (see Fig. 2(a)). CEP stability of the 2nd stage output was verified by means of f-to-2f interferometry in the wavelength range from 690-830 nm (Fig. 2(b)).

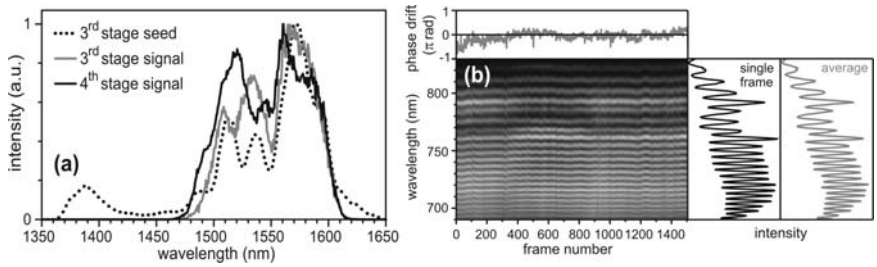

Fig. 2. (a) Spectral properties of the final OPA stages. (b) f-to-2f interferogram reflecting CEP stability measured after the 2nd stage OPA.

The output of the 2nd stage is stretched in a grating stretcher to ~40 ps and a tunable higher-order phase correction is introduced by DAZZLER (Fig.1). The temporally stretched seed is amplified in two final OPA stages (3rd and 4th) using a 50-mJ picosecond pump pulse from the Nd:YAG system. The maximum pulse energy at 1.5 µm before the 60% efficient grating pulse compressor is ~10 mJ, as measured through a bandpass filter that blocks off the 3.6-µm idler wave. µJ-level 10-kHz-repetition-rate pulses after the 2nd OPA stage, pulse stretcher, and DAZZLER were compressed to ~50-fs with the grating compressor and measured with SHG FROG, as shown in Fig.3. Work is now in progress to compress and characterize the multi-mJ 20-Hz pulses at the output of the 4th OPA, the bandwidth of which supports virtually the same pulse duration as the 2nd stage. The output of the multi-mJ IR OPCPA system will be broadened in a noble gas, where we expect to reach up to 4 times higher pulse energies in comparison with a filament/hollow-fiber pumped at λ=0.8 µm.

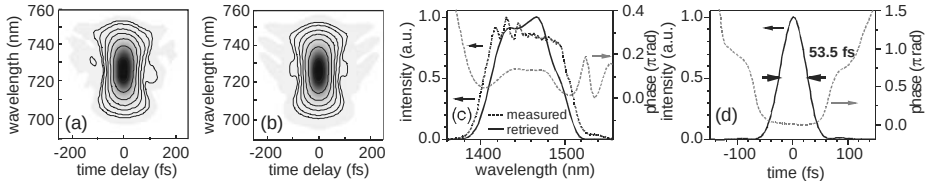

Fig. 3. a) SHG FROG characterization of the stretched and recompressed 1.5 µm pulses: (a) Measured and (b) retrieved SHG FROG trace. (c) Measured spectrum (black dashed), retrieved spectral intensity (black solid) and phase (grey dashed). (d) Retrieved temporal intensity (black solid) and phase (grey dashed) profile indicating a FWHM 53.5 fs pulse duration.

In conclusion, we have developed a prototype CEP-stable IR OPCPA for high field applications which draws on a straightforwardly scalable picosecond pump at the Nd/Yb fundamental wavelength and uses a femtosecond Yb front-end.

Acknowledgements. This work is supported by the Austrian Science Fund (FWF), grants U33-N16 and F1619-N08.

1 A. Dubietis et al., J. Sel. Top. Quantum Electron. **12**, 163 (2006), and references therein.
2 T. Fuji et al., Opt. Lett. **31**, 1103 (2006).
3 C. Vozzi et at., Opt. Express **14**, 10109 (2006); C. Vozzi et at., Opt. Lett. 32, 2957 (2007).
4 P. Colosimo et al., Nature Phys. **4**, 386 (2008); J. Tate et al., Phys. Rev. Lett. **98**, 013910 (2007); K. Schiessl et al., Phys. Rev. Lett. **99**, 253903 (2007); A. Gordon et al., Opt. Express **13**, 2941 (2005); B. Shan et al., Phys. Rev. A **65**, 011804(R) (2001).
5 M. Meckel et al., Science **320**, 1478 (2008); S. N. Yurchenko et al., Phys. Rev. Lett. **93**, 223003 (2004); M. Spanner et al., J. Phys. B **37**, L243 (2004).
6 C. P. Hauri et al., Appl. Phys B **79**, 673 (2004); C. P. Hauri et al., Opt. Lett. **32**, 868 (2006).
7 J. Seres et al., Nature **98**, 433 (2005).
8 D. Kraemer et al., Opt. Lett. **31**, 981 (2006); D. Kraemer et al., JOSA B **24**, 813 (2007).
9 A. Baltuška et al., Phys. Rev. Lett. **88**, 133901 (2002).