Generation of sub-three-cycle, 16 TW light pulses by using noncollinear optical parametric chirped-pulse amplification

Daniel Herrmann,[1,*] Laszlo Veisz,[1] Raphael Tautz,[1] Franz Tavella,[2] Karl Schmid,[1,3] Vladimir Pervak,[3] and Ferenc Krausz[1,3]

[1]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany*
[2]*HASYLAB/DESY, Notkestrasse 85, 22607 Hamburg, Germany*
[3]*Department für Physik, Ludwig-Maximilians-Universität München, Am Coulombwall 1, 85748 Garching, Germany*
**Corresponding author: daniel.herrmann@mpq.mpg.de*

Received May 1, 2009; revised July 16, 2009; accepted July 17, 2009; posted July 21, 2009 (Doc. ID 110877); published August 11, 2009

We present a two-stage noncollinear optical parametric chirped-pulse amplification system that generates 7.9 fs pulses containing 130 mJ of energy at an 805 nm central wavelength and 10 Hz repetition rate. These 16 TW light pulses are compressed to within 5% of their Fourier limit and are carefully characterized by the use of home-built pulse diagnostics. The contrast ratio before the main pulse has been measured as 10^{-4}, 10^{-8}, and 10^{-11} at $t=-3.3$ ps, $t=-5$ ps, and $t=-30$ ps, respectively. This source allows for experiments in a regime of relativistic light–matter interactions and attosecond science. © 2009 Optical Society of America

OCIS codes: 190.4970, 190.7110, 140.4480, 190.4410, 320.7090, 140.3280.

Multiterawatt few-cycle light pulses offer the potential of pushing the frontiers of attosecond science [1,2], quantum coherent control [3], and laser-based particle acceleration [4]. Phase-controlled, intense, few-cycle light pulses can be used to generate powerful isolated attosecond pulses in the extreme UV (XUV) range [5,6], providing photon flux levels adequate for the autocorrelation of XUV pulses and XUV-pump–XUV-probe investigations [7]. For this purpose, carrier-envelope phase effects with few-cycle pulses have been demonstrated [8].

The invention of optical parametric chirped-pulse amplification (OPCPA) offered the prospect of generating few-cycle light pulses by providing sufficient gain-bandwidth to approach the terawatt level [9,10]. Noncollinear OPCPA (NOPCPA) offers many advantages over chirped pulse amplifiers (CPAs), such as a broad gain-bandwidth, high single-pass gain, wavelength tunability, low thermal effects, and a reduced stretching and compression factor [11]. Because of the many challenges, the amplification and compression of few-cycle, terawatt-class pulses were only recently demonstrated in the near-IR [12–15], and few-cycle pulses with less energy in the IR [16,17]. Few-cycle NOPCPA systems require accurate dispersion control during stretching and compression over a broad bandwidth, along with optimum phase-matching conditions, and a high-quality picosecond pump laser. This is needed to achieve an efficient conversion, to ensure a good spatial signal profile, to reach high pulse contrast, and to minimize optical parametric fluorescence (OPF), which can occur within the duration of the pump pulse. NOPCPA is also an efficient method to generate high-quality seed pulses in hybrid NOPCPA–CPA systems, which can eventually reach the petawatt level [18–21].

In this Letter, we report a NOPCPA system, which we call Light-Wave-Synthesizer-20 (LWS-20). It generates 7.9 fs, 130 mJ (16 TW) pulses at an 805 nm center wavelength and 10 Hz repetition rate with high contrast and an excellent beam profile for tight focusing.

The schematic of our LWS-20 NOPCPA setup is presented in Fig. 1. The setup starts with a Ti:sapphire oscillator (Rainbow, Femtolasers GmbH). Its central wavelength is 800 nm, and its bandwidth spans 350 nm with an output pulse energy of 4 nJ and a pulse duration of 5.5 fs at a 10 Hz repetition rate. 60% (2.4 nJ) of the oscillator output is used to generate the seed for the NOPCPA. The remaining 40% (1.6 nJ) is used to seed the flashlamp-pumped Nd:YAG pump laser amplifier (EKSPLA) providing all-optical synchronization.

The seed radiation for the pump amplifier, centered at 1064 nm with several picojoules of energy, is produced by soliton self-frequency shift in a photonic crystal fiber and is subsequently coupled into a regenerative Nd:YAG amplifier [22]. The output of the regenerative amplifier is split, each half being led to

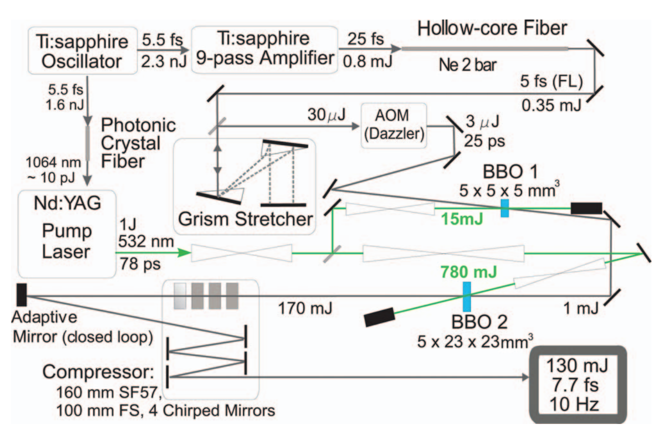

Fig. 1. Schematic layout of the NOPCPA setup.

0146-9592/09/162459-3/$15.00

a Nd:YAG amplifier chain consisting of a double- and two single-pass rods with increasing diameters (8, 12, and 18 mm, respectively). Via noncollinear Type II second-harmonic generation (SHG) in a DKDP crystal, both amplified beams are used to generate a single beam at 532 nm with a conversion efficiency of 45%, comprising pulses with 78 ps duration and 1 J of energy at a repetition rate of 10 Hz as pump for the NOPCPA. This beam is relay imaged onto two BBO crystals, which represent the NOPCPA stages.

In case of OPCPA, the contrast ratio between compressed pulse peak and OPF background strongly depends on the seed energy and on the OPCPA gain [23,24]. To enhance the pulse contrast, we use a new source to generate more energetic seed pulses compared with our previous work [13]. The oscillator output is first led through a 9-pass, 1 kHz Ti:sapphire CPA system (Femtopower Compact Pro, Femtolasers GmbH) and then coupled into a hollow-core fiber filled with neon gas at 2 bar (1500 Torr) absolute pressure, thereby achieving a broadened seed pulse spectrum ranging from 500 to 1000 nm. This spectrum corresponds to a 5 fs Fourier limit, and the pulse contains an energy of 0.35 mJ. We use a negative-dispersion reflection grism pair (10% efficiency) and an acousto-optic modulator (Dazzler, Fastlite, 10% transmission) to stretch the seed pulse to 25 ps with 3 μJ energy at a 10 Hz repetition rate for seeding the single-pass two-stage NOPCPA setup (phase-matching angle θ=23.62°, internal noncollinear angle α=2.23°). The first NOPCPA stage consists of a 5 mm × 5 mm × 5 mm Type I BBO crystal, is pumped by 15 mJ pulses at 532 nm with a peak intensity of 13 GW/cm^2, and amplifies the seed pulse to 1 mJ. The second NOPCPA stage is operated in saturation and consists of a 23 mm × 23 mm × 5 mm Type I BBO crystal and is pumped by 780 mJ pulses at 532 nm with a peak intensity of 8.2 GW/cm^2. After the second NOPCPA stage, the amplified signal pulse energy is 170 mJ with energy fluctuations within 3% rms (limited by 2% rms fluctuations of the pump energy) and negligible OPF. The pump-to-signal conversion is 22%.

Subsequently, the amplified signal beam is expanded from about 16 mm to 140 mm in diameter and compressed in bulk material consisting of 160-mm-long SF57 (Schott) and 100-mm-long fused silica. After the bulk compressor, the beam is down-collimated to a diameter of about 50 mm, sent to an adaptive mirror, and led into a vacuum compression chamber for final compression with four positive-dispersion chirped mirrors. The compressor has a calculated B integral below 1 and a throughput of 75% (including several silver mirrors). The pulse duration and residual phase are measured with a home-built all-reflective second-order single-shot autocorrelator and a home-built single-shot SHG frequency-resolved optical gating device (SHG-FROG). The autocorrelation trace is shown in Fig. 2(a) and reveals a 7.7 fs FWHM pulse duration with a deconvolution factor of 1.35, calculated from the spectrum. The shot-to-shot FWHM pulse duration fluctuations are measured

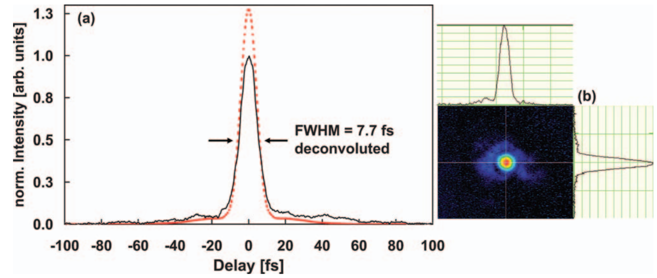

Fig. 2. (a) Second-order single-shot autocorrelation measurement (solid curve) and calculated autocorrelation trace, assuming a Fourier-limited pulse (dotted curve). (b) Focus of the amplified and compressed signal using an f =500 mm achromatic lens; the horizontal and vertical FWHM diameters are 10.58 and 10.25 μm, respectively.

with the single-shot autocorrelator to be within 4% rms. The SHG-FROG inversion results with removed time ambiguity are shown in Fig. 3. A pulse duration of 7.9 fs FWHM is measured while showing a fairly flat phase over the spectrum of the amplified pulse with a FROG error of 0.6%. The Fourier limit typically shows a duration of 7.5 fs FWHM. Therefore, compression is typically achieved to within 5% of the Fourier limit. The main pulse contains 83.5% (taken between the adjacent minima around the main peak)

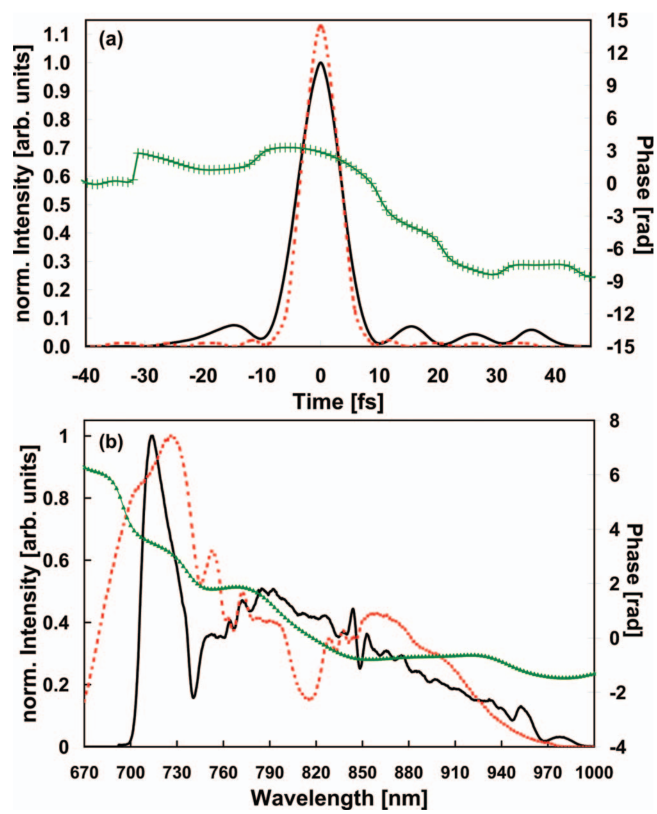

Fig. 3. FROG inversion results of the recompressed 130 mJ pulse (FROG error 0.6%): (a) temporal pulse intensity (solid curve) with removed time ambiguity, residual phase (crosses) and the Fourier-limited pulse (dotted curve). (b) Measured spectrum (696–994 nm, solid curve), retrieved residual phase (triangles), and unamplified stretched seed pulse spectrum (dotted curve).

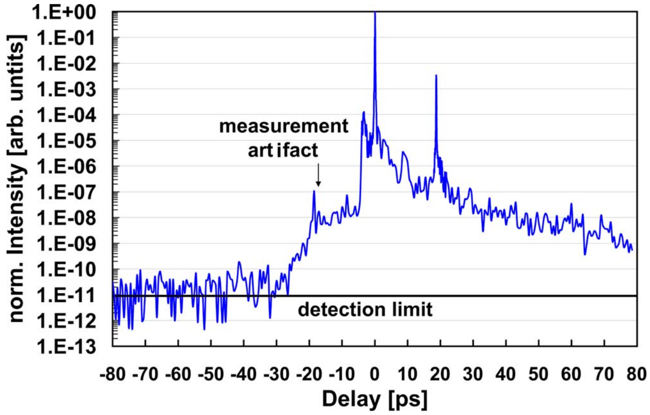

Fig. 4. (Color online) Third-order autocorrelation (negative delays correspond to the pulse leading edge): contrast of the amplified and compressed pulse; the peak at −18.8 ps is a measurement artifact belonging to the corresponding postpulse, and contributions for $t < -30$ ps are background noise.

of the total energy; in the case of a Fourier-limited pulse it is 94.7%. The contrast with respect to the main pulse is measured with an upgraded home-built third-harmonic generation autocorrelator (detection limit 10^{-11} [23]), and the results are shown in Fig. 4. The contrast ratio before the main pulse is measured as 10^{-4} at $t=-3.3$ ps, $\sim 10^{-8}$ at $t=-5$ ps, and $\sim 10^{-11}$ at $t=-30$ ps. We expect the contrast before $t=-30$ ps to be 10^{-12}–10^{-13}, calculated with a contrast of 10^{-7}–10^{-8} for the NOPCPA seed and a subsequent amplification factor of $\sim 10^5$. The postpulse at $t = 18.8$ ps originates from a reflection inside the nine-pass amplifier, while the contribution between $t = -30$ ps and $t=-5$ ps was experimentally verified as a result of amplified spontaneous emission from the front end, which becomes amplified within the temporal window of the NOPCPA pump pulse.

Wavefront aberrations are corrected by using an adaptive mirror in a closed-loop configuration. The focus of the amplified and compressed super-Gaussian signal beam, using an $f=500$ mm achromatic lens, is shown in Fig. 2(b). The M^2 is measured as 2.7, and the Strehl ratio is 0.8.

In summary, we demonstrated for the first time, to our knowledge, the generation of 7.9 fs, 130 mJ (16 TW) light pulses at a central wavelength of 805 nm and a repetition rate of 10 Hz, achieved with our broadband LWS-20 NOPCPA system. This technology permits exploring attosecond physics and high-field interactions in a so far inaccessible parameter regime.

The authors are thankful to Jonas Kolenda (EKSPLA) for invaluable support with the pump laser and Xun Gu for useful discussions about FROG. This work was supported by Deutsche Forschungsgemeinschaft (contract TR18), by the association EURATOM-Max-Planck-Institut für Plasmaphysik, and by the Cluster of Excellence Munich Center for Advanced Photonics (MAP). D. Herrmann is also grateful to Studienstiftung des deutschen Volkes.

References

1. T. Brabec and F. Krausz, Rev. Mod. Phys. **72**, 545 (2000).
2. F. Krausz and M. Ivanov, Rev. Mod. Phys. **81**, 163 (2009).
3. H. Niikura, D. M. Villeneuve, and P. B. Corkum, Phys. Rev. A **73**, 021402(R) (2006).
4. K. Schmid, L. Veisz, F. Tavella, S. Benavides, R. Tautz, D. Herrmann, A. Buck, B. Hidding, A. Marcinkevičius, U. Schramm, M. Geissler, J. Meyer-ter-Vehn, D. Habs, and F. Krausz, Phys. Rev. Lett. **102**, 124801 (2009).
5. G. D. Tsakiris, K. Eidmann, J. Meyer-ter-Vehn, and F. Krausz, New J. Phys. **8**, 19 (2006).
6. E. Goulielmakis, M. Schultze, M. Hofstetter, V. S. Yakovlev, J. Gagnon, M. Uiberacker, A. L. Aquila, E. M. Gullikson, D. T. Attwood, R. Kienberger, F. Krausz, and U. Kleineberg, Science **320**, 1614 (2008).
7. Y. Nomura, R. Hörlein, P. Tzallas, B. Dromey, S. Rykovanov, Zs. Major, J. Osterhoff, S. Karsch, L. Veisz, M. Zepf, D. Charalambidis, F. Krausz, and G. D. Tsakiris, Nat. Phys. **5**, 124 (2009).
8. A. Baltuška, Th. Udem, M. Uiberacker, M. Hentschel, E. Goulielmakis, Ch. Gohle, R. Holzwarth, V. S. Yakolev, A. Scrinzi, T. W. Hänsch, and F. Krausz, Nature **421**, 611 (2003).
9. A. Dubietis, G. Jonusauskas, and A. Piskarskas, Opt. Commun. **88**, 437 (1992).
10. I. N. Ross, P. Matousek, M. Towrie, A. J. Langley, and J. L. Collier, Opt. Commun. **144**, 125 (1997).
11. A. Dubietis, R. Butkus, and A. Piskarskas, IEEE J. Sel. Top. Quantum Electron. **12**, 163 (2006).
12. N. Ishii, L. Turi, V. S. Yakovlev, T. Fuji, F. Krausz, A. Baltuška, R. Butkus, G. Veitas, V. Smilgevičius, R. Danielius, and A. Piskarskas, Opt. Lett. **30**, 567 (2005).
13. F. Tavella, Y. Nomura, L. Veisz, V. Pervak, A. Marcinkevičius, and F. Krausz, Opt. Lett. **32**, 2227 (2007).
14. S. Witte, R. T. Zinkstok, A. L. Wolf, W. Hogervorst, W. Ubachs, and K. S. E. Eikema, Opt. Express **14**, 8168 (2006).
15. S. Adachi, N. Ishii, T. Kanai, A. Kosuge, J. Itatani, Y. Kobayashi, D. Yoshitomi, K. Torizuka, and S. Watanabe, Opt. Express **16**, 14341 (2008).
16. X. Gu, G. Marcus, Y. Deng, T. Metzger, C. Teisset, N. Ishii, T. Fuji, A. Baltuška, R. Butkus, V. Pervak, H. Ishizuki, T. Taira, T. Kobayashi, R. Kienberger, and F. Krausz, Opt. Express **17**, 62 (2009).
17. O. Chalus, P. K. Bates, M. Smolarski, and J. Biegert, Opt. Express **17**, 3587 (2009).
18. E. W. Gaul, M. Martinaz, J. Blakeney, A. Jochmann, M. Ringuette, D. Hammond, S. Marijanovic, R. Escamilla, and T. Ditmire, in *Advanced Solid State Photonics*, OSA Technical Digest Series (CD) (Optical Society of America, 2009), paper WD1.
19. C. Dorrer, I. A. Behishev, A. V. Okishev, J. D. Zuegel, Opt. Lett. **32**, 2143 (2007).
20. I. Jovanovic, C. A. Ebbers, and C. P. J. Barty, Opt. Lett. **27**, 1622 (2002).
21. H. Kiriyama, M. Mori, Y. Nakai, T. Shimomura, M. Tanoue, A. Akutsu, S. Kondo, S. Kanazawa, H. Okada, T. Motomura, H. Daido, T. Kimura, and T. Tajima, Opt. Lett. **33**, 645 (2008).
22. C. Y. Teisset, N. Ishii, T. Fuji, T. Metzger, S. Köhler, R. Holzwarth, A. Baltuška, A. M. Zheltikov, and F. Krausz, Opt. Express **13**, 6550 (2005).
23. F. Tavella, K. Schmid, N. Ishii, A. Marcinkevičius, L. Veisz, and F. Krausz, Appl. Phys. B **81**, 753 (2005).
24. F. Tavella, A. Marcinkevicius, and F. Krausz, New J. Phys. **8**, 219 (2006).