Dispersion management for a sub-10-fs, 10 TW optical parametric chirped-pulse amplifier

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We report the amplification of three-cycle, 8.5 fs optical pulses in a near-infrared noncollinear optical parametric chirped-pulse amplifier (OPCPA) up to energies of 80 mJ. Improved dispersion management in the amplifier by means of a combination of reflection grisms and a chirped-mirror stretcher allowed us to recompress the amplified pulses to within 6% of their Fourier limit. The novel ultrabroad, ultraprecise dispersion control technology presented in this work opens the way to scaling multiterawatt technology to even shorter pulses by optimizing the OPCPA bandwidth. © 2007 Optical Society of America

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High-peak-power few-cycle sources are of interest for a number of applications in nonlinear optics, high-field, and ultrafast science [1]. Few-cycle pulses not only offer high peak powers from compact systems (relative value) but also enable the emergence of entirely new technologies such as the generation and measurement and spectroscopic applications of isolated attosecond pulses and steering the atomic-scale motion of electrons with controlled light fields [2–7] (absolute value). Noncollinear optical parametric amplification offers amplification over spectral ranges sufficiently broad for few-cycle pulse synthesis, but dispersion control during stretching and recompression has remained a major challenge because of the large bandwidth over which the dispersion needs to be compensated with high accuracy. This is one of the reasons why many terawatt-scale optical chirped-pulse amplifiers [8,9] are designed for higher energy amplification and for pulse durations longer than those potentially allowed by the amplification bandwidth. Only recently amplification and adaptive pulse compression of more than 100-THz bandwidths to the few-cycle regime were demonstrated reaching the terawatt regime [10–12].

In this Letter we report the implementation of an ultrabroadband grism-pair stretcher capable of controlling group delay over a dynamic range of tens of picoseconds and a bandwidth exceeding 100 THz. This improvement led to what we believe to be the first sub-10-fs, 10 TW light source ever reported and holds promise for further shortening of multiterawatt light pulses by means of optical parametric amplifier (OPA) bandwidth engineering.

The schematic layout of the our novel stretcher-compressor system is depicted in Fig. 1. The OPA chain is described in previous work [12]. Stretching is implemented by the negative dispersion of a pair of grisms [13]. These hybrid elements combining the dispersive effects of diffraction gratings and prisms were recently demonstrated to be capable of introducing near-linear dispersion with high throughput over a bandwidth of 60 nm in the near infrared [13–15]. Here we demonstrate that they can also control optical delay efficiently over a bandwidth of 300 nm in the same spectral range. Our positive-dispersion compressor is composed of glass blocks and chirped mirrors (CM2). The latter are used for final compression to prevent excessive nonlinear effects in the glass compressors. Residual higher-order dispersion of the system is compensated by another pair of chirped mirrors (CM1) and a programmable acousto-optic dispersive filter (AODF), dubbed Dazzler [16].

The grism stretcher is designed to compensate for the dispersion of (1) the glass compressor (160 mm of SF57 and 100 mm of fused silica), (2) the BBO crystals in the optical parametric chirped-pulse amplifier (OPCPA) chain (a total of 15-mm path length), and (3) the acousto-optical filter (43 mm of TeO_2) at the central wavelengths of 850 nm of our amplifier chain.

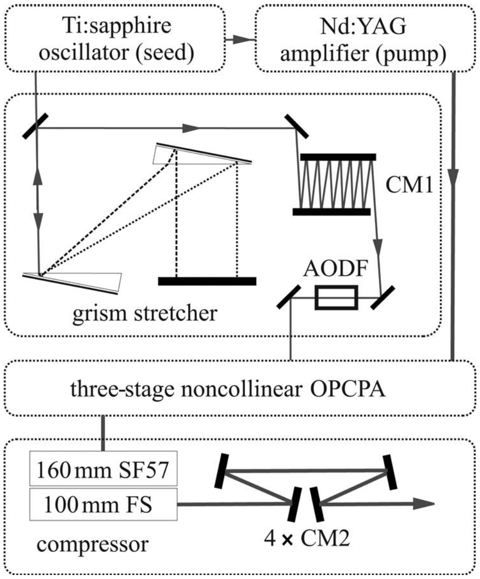

Fig. 1. Optical layout of the OPCPA experimental setup.

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Our numerical studies revealed best performance for normal incidence and low-groove-density gratings. Grisms composed of standard 300 lines/mm gold-coated ruled gratings (Newport) and antireflection-coated SF11 prisms having an apex angle of 18° turned out to be the optimum choice for minimizing high-order dispersion in the near infrared. To achieve the required negative dispersion over the whole bandwidth of nearly 300 nm, the deviation angle on the grism grating is ~20°, this being reasonably close to the Littrow angle for high efficiency.

The calculated coefficients of the Taylor expansion of the spectral phase delay at $\lambda_0=2\pi c/\omega_0=850$ nm, $D_i=[\partial^i\phi(\omega)/\partial\omega^i]|_{\omega=\omega_0}$, of our grism-pair stretcher are $D_2=-5.48\times10^4$ fs^2 (group-delay dispersion), $D_3=-1.33\times10^5$ fs^3 (third-order dispersion), and $D_4=1.00\times10^4$ fs^4 (fourth-order dispersion). The spectral phase $\phi(\omega)$ is calculated by ray tracing and taking into account the wavelength-dependent phase shift caused by the gratings in the stretcher setup [17]. The overall material dispersion introduced by the above listed components of the amplifier chain, the compressor, and the Dazzler are calculated as $D_2=5.47\times10^4$ fs^2, $D_3=3.76\times10^4$ fs^3 and $D_4=1.00\times10^4$ fs^4. From these results it follows that the fourth-order dispersion is fully compensated, while the residual second-order dispersion is sufficiently low to be corrected by the Dazzler. However, for residual third-order dispersion additional measures are required. The residual third-order dispersion is way too high to be compensated by the Dazzler alone if reasonably high diffraction efficiency is required. To this end, we designed and fabricated a pair of chirped mirrors introducing 600 fs^3/bounce over the spectral range of 650–1050 nm. Due to the relatively high losses per bounce we use only 20 bounces off these mirrors (CM1 in Fig. 1) to correct for a fraction of the residual third-order dispersion of the OPCPA system. The measured absolute efficiency of the grism stretcher combined with chirped mirrors is 21% for the entire amplified signal bandwidth. The lower transmission efficiency of the grism stretcher compared with the ~40% throughput of the previous stretcher results in a lower seed energy available for the first amplification stage, which in turn decreased the contrast of the amplified and compressed pulse [18]. Further throughput optimization of this newly designed stretcher and development of a more powerful front end are under way.

The dispersive system composed of the grism pair and the chirped-mirror pair CM1 stretches the 5 fs pulses from the Ti:sapphire oscillator by approximately a factor of 10,000 to pulses with a duration of 50 ps. Propagation through the Dazzler recompresses the pulses to a duration of ~40 ps before entering the amplifier chain. With our current system, the stretched pulse duration in the amplifier chain can be tuned between 5 and 60 ps (by changing the horizontal and vertical separation between the grisms) without compromising high-order dispersion compensation. For our current experiments, we have chosen 40 ps, as a trade-off between maximum gain bandwidth and maximum conversion efficiency (for a Gaussian pump pulse of 100-ps duration).

The spectrum transmitted by the stretcher is shown in Fig. 2 (solid curve). Comparison with the seed spectrum (shaded gray contour) reveals that the grism-pair increasingly suppresses spectral components at wavelengths beyond 1 μm, mainly due to the roll-off in grating diffraction efficiency. Fourier transformation of the amplified spectrum (Fig. 2, dashed curve) yields pulse duration of 8 fs [full width at half-maximum (FWHM)]. It is important to mention that in the current interaction geometry the amplification bandwidth (~720–1020 nm) of 5 mm long BBO crystals supports a transform-limited pulse duration of 7.6 fs. The amplified spectrum is smoother as compared with that obtained with our previous pulse stretcher [12], with the fine structure largely attributed to superfluorescence (approximately 30 mJ out of the 110 mJ of the amplified output). It is important to note that the new stretcher is easy to align, versatile, and compact. No residual spatial chirp could be detected by measuring the stretched pulse spectrum at different points in the beam cross section.

The amplified pulses after compression were measured with a single-shot spectral interferometer for direct electric-field reconstruction (SPIDER) [19,20]. The SPIDER apparatus was designed for measuring pulses down to the 5 fs in duration and previously tested in this regime by the pulse duration measurements on an ultrabroadband Ti:sapphire oscillator. Figure 3(a) shows the retrieved spectrum and spectral phase, and Fig. 3(b) shows the reconstructed intensity envelope in time. The compressed pulse has a nearly constant phase over the entire bandwidth of the pulse, resulting in a pulse duration of 8.5 fs, which is within 6% of the Fourier limit. The amplified pulse compression was reproducible, and to our knowledge the shot-to-shot pulse duration fluctuation was measured for the first time for OPCPA with a single-shot SPIDER apparatus [21]. The single-shot SPIDER is a key component for fast and reliable system optimization of a low-repetition-rate (10 Hz) system and measurement of the pulse duration fluctuation. For the present system the rms deviation

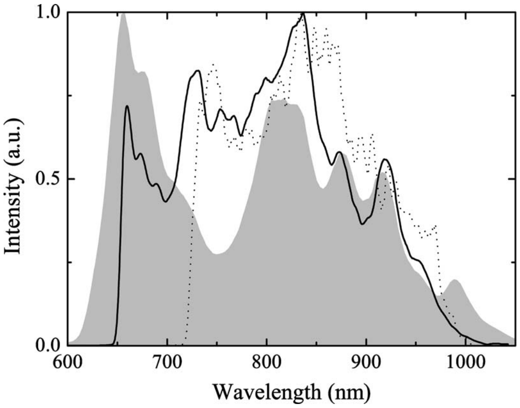

Fig. 2. Pulse spectrum evolution in the OPCPA system: at the oscillator output (shaded gray contour), after the grism-pair stretcher (solid curve), and after amplification (dashed curve).

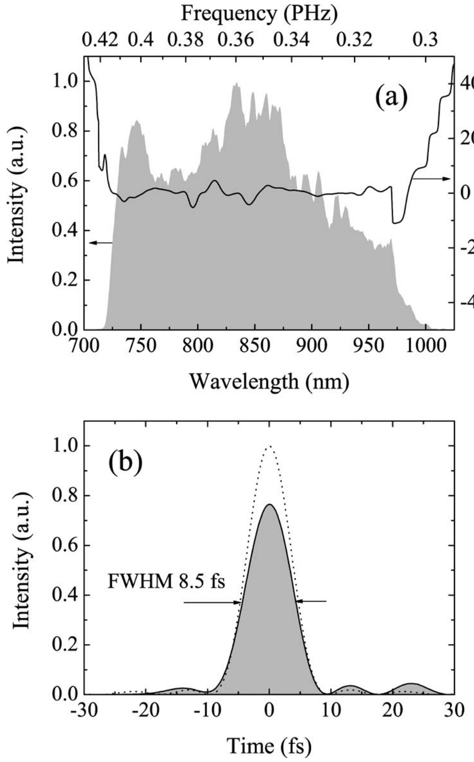

Fig. 3. Amplified pulse after compression: (a) measured amplified pulse spectrum (shaded contour) and retrieved group delay (solid curve), (b) recompressed 80-mJ pulse. The dotted curve corresponds to the intensity profile of a transform-limited pulse (FWHM=8 fs) of the amplified spectrum.

was measured to be 4.7%. This comes in combination with a good energy stability; its rms value was evaluated as 4.5%.

In conclusion, we have demonstrated an ultrabroadband dispersion management system, drawing on a reflection grism pair for stretching, glass blocks for high-throughput compression, and chirped mirrors and a Dazzler for high-order dispersion control, offering optical delay control over the spectral range of 720–1000 nm. Its first application in a noncollinear OPCPA system yielded gain-bandwidth-limited three-cycle 10 TW pulses at a repetition rate of 10 Hz. The present system is scalable in energy and in duration. The maximal available sizes of BBO crystals and compressor glass blocks limit the amplified pulse energy to approximately 500 mJ, whereas thinner BBO crystals can be used to enhance the amplification bandwidth and reduce compressed pulse duration until 6.2 fs. This technology will permit exploring high-field interactions in previously inaccessible parameter regimes.

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References

1. T. Brabec and F. Krausz, Rev. Mod. Phys. **72**, 545 (2000).
2. M. Hentschel, R. Kienberger, Ch. Spielmann, G. A. Reider, N. Milosevic, T. Brabec, P. Corkum, U. Heinzmann, M. Drescher, and F. Krausz, Nature **414**, 509 (2001).
3. M. Drescher, M. Hentschel, R. Kienberger, M. Uiberacker, V. Yakovlev, A. Scrinzi, Th. Westerwalbesloh, U. Kleineberg, U. Heinzmann, and F. Krausz, Nature **419**, 803 (2002).
4. A. Baltuska, Th. Udem, M. Uiberacker, M. Hentschel, E. Goulielmakis, Ch. Gohle, R. Holzwarth, V. S. Yakovlev, A. Scrinzi, T. W. Hänsch, and F. Krausz, Nature **421**, 611 (2003).
5. R. Kienberger, E. Goulielmakis, M. Uiberacker, A. Baltuska, V. Yakovlev, F. Bammer, A. Scrinzi, Th. Westerwalbesloh, U. Kleineberg, U. Heinzmann, M. Drescher, and F. Krausz, Nature **427**, 817 (2004).
6. M. F. Kling, Ch. Siedschlag, A. J. Verhoef, J. I. Khan, M. Schultze, Th. Uphues, Y. Ni, M. Uiberacker, M. Drescher, F. Krausz, and M. J. J. Vrakking, Science **312**, 246 (2006).
7. G. Sansone, E. Benedetti, F. Calegari, C. Vozzi, L. Avaldi, R. Flammini, L. Poletto, P. Villoresi, C. Altucci, R. Velotta, S. Stagira, S. De Silvestri, and M. Nisoli, Science **314**, 443 (2006).
8. A. Dubietis, R. Butkus, and A. Piskarskas, IEEE J. Sel. Top. Quantum Electron. **12**, 163 (2006).
9. O. V. Chekhlov, J. L. Collier, I. N. Ross, P. K. Bates, M. Notley, C. Hernandez-Gomez, W. Shaikh, C. N. Danson, D. Neely, P. Matousek, and S. Hancock, Opt. Lett. **31**, 3665 (2006).
10. S. Witte, R. T. Zinkstok, A. L. Wolf, W. Hogervorst, W. Ubachs, and K. S. E. Eikema, Opt. Express **14**, 8168 (2006).
11. T. Fuji, N. Ishii, C. Y. Teisset, X. Gu, Th. Metzger, A. Baltuska, N. Forget, D. Kaplan, A. Galvanauskas, and F. Krausz, Opt. Lett. **31**, 1103 (2006).
12. F. Tavella, A. Marčinkevicius, and F. Krausz, Opt. Express **14**, 12822 (2006).
13. S. Kane and J. Squier, J. Opt. Soc. Am. B **14**, 661 (1997).
14. D. M. Gaudiosi, E. Gagnon, A. L. Lytle, J. L. Fiore, E. A. Gibson, S. Kane, J. Squier, M. M. Murnane, H. C. Kapteyn, R. Jimenez, and S. Backus, Opt. Express **14**, 9277 (2006).
15. E. A. Gibson, D. M. Gaudiosi, H. C. Kapteyn, R. Jimenez, S. Kane, R. Huff, Ch. Durfee, and J. Squier, Opt. Lett. **31**, 3363 (2006).
16. F. Verluise, V. Laude, Z. Cheng, Ch. Spielmann, and P. Tournois, Opt. Lett. **25**, 575 (2000).
17. E. B. Treacy, IEEE J. Quantum Electron. **5**, 454 (1969).
18. F. Tavella, K. Schmid, N. Ishii, A. Marcinkevicius, L. Veisz, and F. Krausz, Appl. Phys. B **81**, 753 (2005).
19. C. Iaconis, V. Wong, and I. A. Walmsley, IEEE J. Sel. Top. Quantum Electron. **4**, 285 (1998).
20. C. Iaconis and I. A. Walmsley, Opt. Lett. **23**, 792 (1998).
21. T. M. Shuman, M. E. Anderson, J. Bromage, C. Iaconis, L. Waxer, and I. A. Walmsley, Opt. Express **5**, 134 (1999).