Pulse compression with time-domain optimized chirped mirrors

P. Dombi[§,¶], V. S. Yakovlev[*], K. O'Keeffe[§], T. Fuji[*], M. Lezius[§], G. Tempea[§, #]

[§]Photonics Institute, Christian Doppler Laboratory, Vienna University of Technology,
Gusshausstr. 27/387, A-1040 Wien, Austria Phone: + 43 1 58801 38725 Fax: + 43 1 58801 38799

[¶]Research Institute for Solid-State Physics and Optics
Konkoly-Thege M. út 29-33, H-1121 Budapest, Hungary, Phone: +36 1 392 2222 / 3609, Fax: +36 1 3922215

**Max-Planck-Institute of Quantum Optics*
Hans-Kopfermann-Strasse 1, D-85748 Garching Germany
Phone: +49 89 32905 601, Fax: +49 89 32905 649

[#]Femtolasers Produktions GmbH
Fernkorngasse 10, A-1100 Vienna, Austria
Phone: +43 1 503 7002 40, Fax: +43 1 503 7002 99
gabriel.tempea@femtolasers.com

http://www.femtolasers.com

Abstract: Dispersive optical interference coatings (chirped mirrors – CMs) are designed by computer optimization of an analytically calculated initial multilayer. Traditionally, the relevant properties of the CM (reflectance and the frequency-dependence of the phase shift upon reflection) are optimized to match frequency-domain targets. We propose a novel target function that quantifies directly the capability of a multilayer to control the temporal shape of the reflected optical pulse. Employing this time-domain analysis/optimization one can design dispersive multilayers having air as medium of incidence and supporting the generation of pulses with durations in the sub-5-fs-range, as demonstrated in a proof-of-principle compression experiment.

OCIS codes: (320.5520) Pulse compression; (320.7160) Ultrafast technology

---

References and links

1. R. Szipöcs, K. Ferencz, C. Spielmann, F. Krausz, "Chirped multilayer coatings for broadband dispersion control in femtosecond lasers," Opt. Lett. **19**, 201-203 (1994).
2. P. F. Moulton, "Spectroscopic and laser characteristics of Ti:Al_2O_3," J. Opt. Soc. Am. B **3,** 125-133 (1986).
3. R. Ell, U. Morgner, F. X. Kärtner, J. G. Fujimoto, E. P. Ippen, V. Scheuer, G. Angelow, T. Tschudi, M. J. Lederer, A. Boiko, B. Luther-Davies, "Generation of 5 fs pulses and octave-spanning spectra directly from a Ti:sapphire laser," Opt. Lett. **26**, 373-375 (2001).
4. T. Fuji, J. Rauschenberger, A. Apolonski, V. S. Yakovlev, G. Tempea, F. Krausz, T. Udem, C. Gohle, T. W. Hänsch, W. Lehnert, M. Scherer, "Monolithic carrier-envelope phase stabilization scheme," Opt. Lett. **30**, 332-334 (2005).
5. O. D. Mücke, R. Ell, A. Winter, J. W. Kim, J. R. Birge, L. Matos, F. X. Kärtner, "Self-referenced 200 MHz octave-spanning Ti:Sapphire laser with 50 attosecond carrier-envelope phase jitter," Opt. Express **13,** 5163-5169 (2005).
6. M. Nisoli, S. DeSilvestri, O. Svelto, "Generation of high energy 10 fs pulses by a new pulse compression technique," Appl. Phys. Lett. **68**, 2793-2795 (1996).
7. M. Nisoli, S. DeSilvestri, O. Svelto, R. Szipöcs,K. Ferencz, Ch. Spielmann, S. Sartania, F. Krausz, "Compression of high-energy laser pulses below 5 fs," Opt Lett **22**, 522-524 (1997).

#9250 - $15.00 USD Received 24 October 2005; revised 7 December 2005; accepted 14 December 2005

8. G. Tempea and T. Brabec, "Nonlinear source for the generation of high-energy few-cycle optical pulses," Opt. Lett. **23**, 1286-1288 (1998).
9. A. Suda, M. Hatayama, K. Nagasaka, K. Midorkawa, "Generation of sub-10-fs, 5-mJ-optical pulses using a hollow fiber with a pressure gradient, " Appl. Phys. Lett. **86,** 111116 (2005).
10. C. Roland and P. B. Corkum, "Compression of high-power optical pulses," J. Opt. Soc. Am. B **5**, 641-647 (1988).
11. E. Mével, O. Tcherbakoff, F. Salin, E. Constant, "Extracavity compression technique for high-energy femtosecond pulses**,** " J. Opt. Soc. Am. B **20**, 105 (2003).
12. C. P. Hauri, W. Kornelis, F.W. Helbing, A. Heinrich, A. Couairon, A. Mysyrowicz, J. Biegert, U. Keller, "Generation of intense, carrier-envelope phase-locked few-cycle laser pulses through filamentation," Appl. Phys. B **79**, 673-677 (2004).
13. F. X. Kärtner, N. Matuschek, T. Schibli, U. Keller, H. A. Haus, C. Heine, R. Morf, V. Scheuer, M. Tilsch, T. Tschudi, "Design and fabrication of double-chirped mirrors," Opt. Lett. **22**, 831-833 (1997).
14. F. X. Kärtner, U. Morgner, R. Ell, T. Schibli, J. G. Fujimoto, E. P. Ippen, V. Scheuer, G. Angelow, T. Tschudi, "Ultrabroadband double-chirped mirror pairs for generation of octave spectra," J. Opt. Soc. Am. B **18**, 882-885 (2001).
15. V. Laude and P. Tournois, "Chirped-mirror pairs for ultra-broadband dispersion control," in: Proceedings of the Conference on Lasers and Electro-Optics CLEO`99 (Optical Society of America, Washington, D.C., 1999), 187 (1999).
16. N. Matuschek, L. Gallmann, D. H. Sutter, G. Steinmeyer, U. Keller, "Back-side-coated chirped mirrors with ultra-smooth broadband dispersion characteristics," Appl. Phys. B **71**, 509-522 (2000).
17. R. Szipöcs and A. Köházi-Kis, "Theory and design of chirped dielectric laser mirrors," Appl. Phys. B **65**, 115 (1997).
18. G. Tempea, F. Krausz, Ch. Spielmann, K. Ferencz, "Dispersion control over 150 THz with chirped dielectric mirrors," IEEE J. Sel. Top. Quantum Electron. **4**, 193 (1998).
19. G. Tempea, V. Yakovlev, B. Bacovic, F. Krausz, K. Ferencz, "Tilted-front-interface chirped mirrors," J. Opt. Soc. Am. B **18**, 1747 (2001).
20. B. Schenkel, J. Biegert, U. Keller, C. Vozzi, M. Nisoli, G. Sansone, S. Stagira, S. De Silvestri, O. Svelto, "Generation of 3.8-fs pulses from adaptive compression of a cascaded hollow fiber supercontinuum," Opt. Lett. **28,** 1987-1989 (2003).
21. K. Yamane, Z. Zhang, K. Oka, R. Morita, M. Yamashita, A. Suguro, "Optical pulse compression to 3.4 fs in the monocycle region by feedback phase compensation," Opt. Lett. **28,** 2258-2260 (2003).
22. J. A. Dobrowolski, A. V. Tikhonravov, M. K. Trubetskov, B. T. Sullivan, P. G. Verly, "Optimal single-band normal-incidence antireflection coatings," Appl. Opt. **35**, 644-658 (1996).
23. G. Steinmeyer, "Brewster-angled chirped mirrors for high-fidelity dispersion compensation and bandwidths exceding one optical octave," Opt. Express **11**, 2385-2396 (2003).
24. G. Tempea, V. Yakovlev, F. Krausz "Interference coatings for ultrafast optics," in: "Optical Interference Coatings," (N. Kaiser and H. Pulker, editors), in: Springer Series in Optical Sciences, Springer, Berlin, Heidelberg (2003).
25. G. Steinmeyer, "Dispersion oscillations in ultrafast phase-correction devices," IEEE J. Quantum Electron. **39,** 1027 (2003).
26. G. Tempea and V. S. Yakovlev, "Time-domain analysis of multilayer mirrors for ultrafast optics," Optical Interference Coatings Topical Meeting 27.06.2004-02.07.2004, Tucson (AZ), USA (2004).
27. V. Yakovlev and G. Tempea, "Chirped mirror optimization," Appl. Opt. **41,** 6514 (2002).
28. S. Sartania. Z. Cheng, M. Lenzner, G. Tempea, Ch. Spielmann, F. Krausz, K. Ferencz, "Generation of 0.1-TW 5-fs optical pulses at a 1-kHz repetition rate," Opt. Lett. **22**, 1562-1564 (1997).
29. V. S. Yakovlev, P. Dombi, G. Tempea, C. Lemell, J. Burgdörfer, T. Udem, A. Apolonski, "Phase-stabilized 4-fs pulses at the full oscillator repetition rate for a photoemission experiment," Appl. Phys. B **76**, 329-333 (2003).

---

1. Introduction

Dispersion management with multilayer reflectors [1] has become the method of choice in laser systems capable to generate sub-10-fs pulses. CMs provide sufficiently accurate means of controlling the group delay dispersion (GDD, the second derivative of the phase shift on reflection with respect to the angular frequency) to support the compression of coherent continua to pulses lasting only few optical cycles (an optical cycle at the carrier wavelength of 800 nm lasts ≈ 2.7 fs). Furthermore, the compactness and user-friendliness of these components make them attractive for industrial applications.

#9250 - $15.00 USD Received 24 October 2005; revised 7 December 2005; accepted 14 December 2005

Few-cycle optical pulses have been generated so far mainly with Ti:sapphire-based laser systems at a center wavelength of 800 nm. This active medium has exceptional properties (thermal conductivity, upper-level lifetime and first of all gain bandwidth [2]) that also allow the generation of octave-spanning pulses directly from laser oscillators [3-5]. Gain narrowing in amplifier chains limits the shortest duration of pulses with energies in the mJ and multi-mJ range to ≈ 20 fs. Extremely efficient spectral broadening techniques have been devised, enabling the generation of ultra-broadband coherent continua with energetic pulses. These methods rely on nonlinear propagation either in a waveguide (filled with a noble gas at constant pressure [6-8] or exhibiting a pressure gradient [9]) or in bulk media [10-12]. Irrespectively of the mechanism used for spectral broadening, the generated continua carry a frequency dependent spectral phase (dubbed "chirp") that needs to be removed in a dispersive delay line in order to compress the pulses as close to the Fourier limit as possible. In most recent implementations of pulse compression techniques, dispersive ("chirped") mirrors were used in the negative dispersion delay lines. This choice was driven by the advantages CMs offer as compared to grating or prism pairs: increased bandwidth, improved control of higher order dispersion, low losses, compactness and stability. Despite of tremendous progress in the design and manufacturing of CMs [13-19], the bandwidth of these components still does not cover the full spectrum of coherent continua, limiting thus the achievable pulse duration to 4-5 fs. This result could be further improved only by using adaptive light modulators [20-21] that dramatically increase the complexity of the setup and limit the maximum energy of the pulses.

2. Dispersive mirror design: current status

The frequency dependence of the group delay experienced by a broadband pulse upon reflection off a CM can be controlled by means of the penetration depth of the different spectral components in the multilayer, as schematically depicted in Fig.1. The most challenging problem one is confronted with in the design of CMs is the undesired resonant trapping of certain wave packets within the multilayer or between the inner interfaces of the mirror and its front surface (towards the medium of incidence /air/). This phenomenon rooted in impedance mismatch leads to large variations of the group delay and consequently to large fluctuations of the GDD over the high reflectance range of the mirror. Initially computer optimization [1] and later analytical design methods [13,17,18] have been efficiently employed to avoid resonant trapping *within* the multilayer. Yet, undesired interference between the beam partially reflected at the front interface (to air) and beams reflected at different depths from within the multilayer seemed to set the ultimate bandwidth-limitation. In order to suppress the GDD-fluctuations, an antireflection (AR) coating or a narrow band-stop filter have to be deposited on top of the mirror. The residual reflectance at the air-interface must be less than 10^{-3} %. A state-of-the-art AR-coating [22] can fulfill this requirement over not more than 150-160 THz at 800 nm, thus limiting the bandwidth of the CMs to this value.

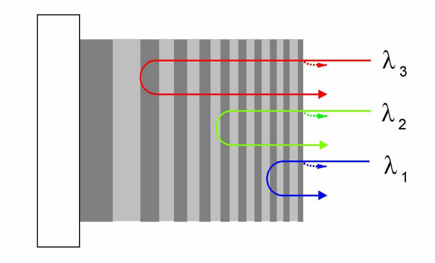

Fig. 1. Schematic representation of a CM. In order to introduce negative GDD, $\lambda_1 < \lambda_2 < \lambda_3$.

#9250 - $15.00 USD Received 24 October 2005; revised 7 December 2005; accepted 14 December 2005

The problem of impedance mismatch can be overcome by means of designs employing glass as medium of incidence. These solutions require either the coating to be placed on the back-side of a thin non-plane-parallel substrate [16] or a thin glass wedge to be attached (e.g. by optical contacting) on the mirror surface [19]. Both types of components require involved post-processing, their aperture size is limited and the amount of GDD they can compensate is smaller as with standard CMs, since the beam has to propagate through the dispersive substrate or front wedge. Alternatively, a mirror-pair can be designed such that the GDD-oscillations exhibited by each mirror compensate one another, resulting in a smoother GDD-curve [14,15], or a single mirror can be designed for the Brewster angle [23]. All these approaches were concerned with minimizing the amplitude of the GDD-oscillations exhibited by the multilayer. Investigating the performance of the mirror in the time domain, we show that under certain conditions extremely large oscillations of the GDD from the target curve can be tolerated without compromising the quality of the reflected pulses.

3. Time domain analysis and design of chirped mirrors

Traditionally, the relevant properties of the CM (reflectance and the frequency dependence of the phase shift upon reflection) are optimized to match frequency-domain targets. We propose a novel target function that quantifies the capability of a multilayer to control the temporal shape of the reflected optical pulse. Recently, the time-domain (fast Fourier transform based) analysis of the mirrors performance has been increasingly employed [24-27]. Drawing on this time-domain analysis/optimization one can design dispersive multilayers having air as medium of incidence and supporting the generation of pulses with durations in the 4-fs-range.

A simple calculation of the effect the reflection off a CM has on the shape of the reflected pulse reveals that the GDD of the mirror may exhibit very large fluctuations around the target value (the target value is obviously corresponding to the chirp carried by the pulse to be compressed upon reflection, with reverse sign) without significantly affecting the duration of the reflected (compressed) pulse. This is true provided that: i) the *averaged* (smoothed) GD/GDD-curve follows closely the target curve and ii) the fluctuations of the GDD as a function of frequency are quasi-periodic and have a period much smaller than the width of the pulse's spectrum. With these relaxed constraints, the design of chirped mirrors *for air as the medium of incidence*, having a bandwidth of more than one optical octave and supporting the generation of pulses in the 4-fs-range becomes possible. Any of the available algorithms [13,17,18] can be employed for calculating a starting structure with a bandwidth of > 500 nm. If a constant (or slowly varying) GDD-value is set as target over this wavelength range and the medium of incidence is air, numerical optimization algorithms will systematically fail to find a solution satisfying a reasonable convergence criterion (e.g. deviations smaller than 50% of the target value). If a merit function comparing the shape of the reflected pulse to that of a bandwidth-limited pulse is employed, a standard gradient-like optimization algorithm would quickly converge to a design that exhibits very large, periodic GDD-oscillations but supports a pulse duration very close to the ideal one.

The effect of the reflection on the temporal pulse shape can be calculated by multiplying the complex spectrum of the incident pulse with the transfer function of the mirror $H(\omega) = r(\omega)\exp[i\varphi_r(\omega)]$, where $r(\omega)$ and $\varphi_r(\omega)$ are the amplitude reflectance and the phase shift upon reflection, respectively. Fourier transforming the product will yield the temporal shape of the reflected pulse. A merit function can be designed to quantify the deviation of the shape of the reflected pulse from that of the ideally compressed (bandwidth limited) one (Tempea et al. 2003).

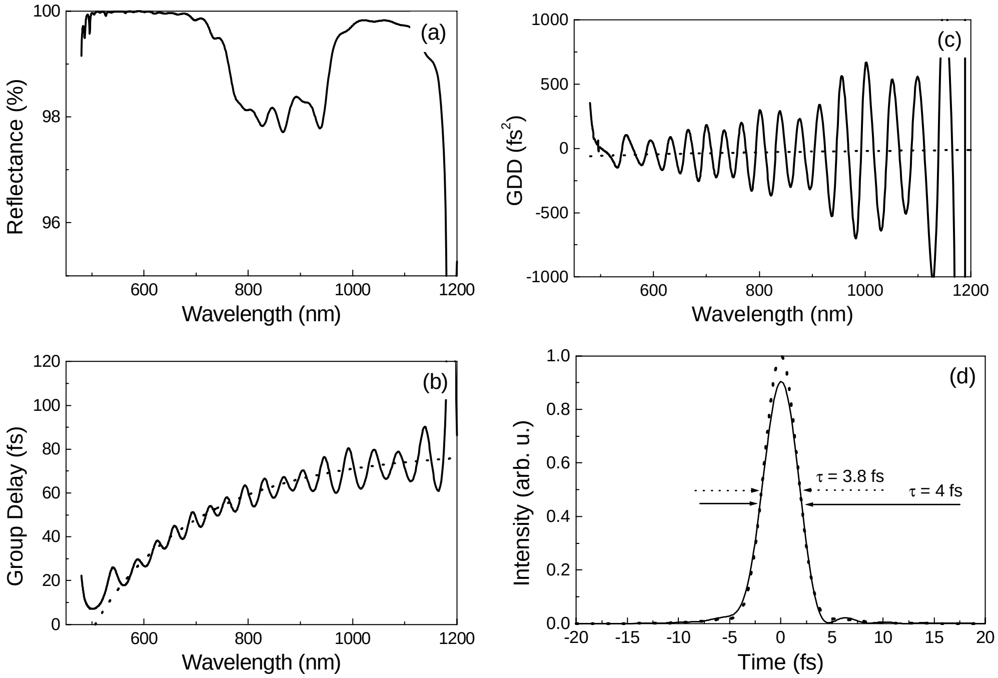

Fig. 2. Reflectance (a), GD (b) and GDD (c) of a chirped mirror consisting of 80 layers of SiO_2 and TiO_2, designed for air as the medium of incidence. The dots in (b) and (c) depict the GD, respectively GDD that the mirror should introduce in order to reflect a bandwidth-limited pulse. The panel (d) shows the intensity envelopes of the bandwidth limited pulse (dots) and of the pulse reflected 3 times off the mirror (full line). The incident pulse (not depicted) carries a chirp corresponding to the GDD given by the dots in panel (c), with reverse sign.

4. Design example

In Fig. 2 the reflectance (a), group delay (b) and group delay dispersion (c) of a mirror designed to compensate the dispersion of 0.83 mm of fused silica are depicted. The medium of incidence is air; thus a small fraction of the beam (≈ 0.2 %) is reflected at the front interface. Interference between this beam and beams partially reflected at the inner interfaces of the multilayer causes large GD and GDD-oscillations (Fig. 2b, 2c). It should be however stressed that the GD and GDD curves oscillate around the target value, i.e. their smoothened values follow the target curves (depicted by the dots in Fig. 2b and Fig. 2c). At the output of a typical hollow fiber compressor [28] the dispersion corresponding to ≈ 2.5 mm of fused silica needs to be compensated in order to compress the spectrally broadened pulses. This can be achieved by taking 3 bounces off the designed mirror. If the multiple (3 X) reflection of a 3.8-fs super-Gaussian pulse carrying the chirp to be compensated by the mirrors (with reverse sign) is simulated as described in the previous paragraph, one finds that the duration of the reflected pulse is only by 5 % larger than that of the bandwidth limited one (Fig. 2d). The large GDD-oscillations result merely in the emergence of small satellite pulses (containing ≈ 4 % of the incident energy and having an intensity lower by a factor of more than 10^{-2} as compared to that of the main reflected pulse) at a delay of ≈ 50 fs. This behavior seems less surprising if we note that the mirror introduces a group delay of ≈ 50 fs at the carrier wavelength of the pulse (750 nm). Thus, the "main" pulse reflected by the multilayer is expected to be delayed by 50 fs with respect to the pre-pulse reflected at the air-interface; this corresponds fairly well to the delay between the central pulse and the satellites observed in the simulation. The mechanism leading to the emergence of pre- and post-pulses has been thoroughly investigated in [25].

5. Pulse compression

Employing a multi-pass chirped pulse amplifier and two hollow fibers filled with noble gas we have generated a continuum covering more than one optical octave in the visible and near infrared spectral region (Fig. 3). A fraction of 70 µJ from the 0.4-mJ, 10-fs output of an amplifier / hollow fiber compressor has been coupled into a 7-cm-long hollow fiber with a diameter of 166 µm, filled with Krypton at a pressure of 2 Bar. The throughput of the fiber amounts to 50%. The amplifier / hollow fiber laser system used for seeding the second hollow fiber was described in detail previously [28]. Dispersive time-domain optimized chirped mirrors have been used for compressing this continuum; a pulse duration clearly below 5 fs has been inferred from the second order interferometric autocorrelation. This experiment was aimed at demonstrating the capability of mirrors with large GDD-oscillations to generate short, undistorted pulses rather than claiming a record pulse duration. The interferometric autocorrelation clearly shows that the pulses are pedestal-free. Although predicted by the theory, neither pre- nor post-pulses could be detected. This is not surprising, since their intensity is predicted to be two orders of magnitude lower than that of the main pulse. Further characterization employing SPIDER or FROG has to be performed in order to confirm the sub-5-fs pulse duration.

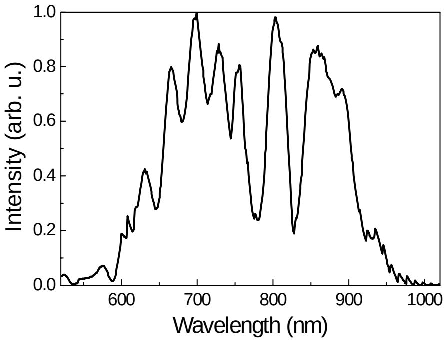

Fig. 3. Spectrum generated by broadening 10-fs, 70-µJ pulses by means of nonlinear propagation in a Krypton-filled (2 bar) hollow fiber. This spectrum corresponds to a bandwidth-limited pulse duration of 4.26 fs FWHM.

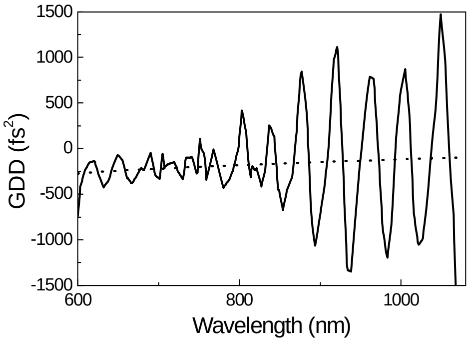

Fig. 4. Total measured GDD of the chirped mirror compressor (full line) and the target-GDD of the ideal compressor, corresponding to the estimated chirp carried by the broadbad continuum.

Figure 4 shows the total GDD of the compressor (6 mirror bounces in total). The GDD of the chirped mirrors has been measured in the range 600 nm to 1100 nm by means of white light interferometry. The mirrors were designed to provide dispersion compensation in the range 550 nm – 1150 nm but the limited bandwidth of the white light interferometer has prevented their characterization over this full spectral range. The total GDD oscillates around the target GDD (represented by dots in Fig. 4) with an amplitude well in excess of 1000 fs^2 on the long-wavelength side. The spectrum in Fig. 3 corresponds to bandwidth-limited pulses having a duration of 4.3 fs FWHM. Figure 5(a) depicts the second order interferometric autocorrelation of the bandwidth-limited pulse calculated from the measured spectrum. The measured autocorrelation (Fig. 5(b)) is strikingly similar to the calculated one, prompting us to the conclusion that the pulse duration is shorter than 5 fs.

The autocorrelation trace depicted in Fig. 5(a) has been recorded with a dispersion-balanced autocorrelator specially designed for the characterization of extremely short pulses (this device is thoroughly described in [29]). In order to minimize the internal dispersion of the autocorrelator, a thin pellicle beam splitter was used; furthermore, a 10-µm BBO was employed for frequency doubling in order to enhance the phase matching bandwidth. The pellicle beam splitter is uncoated and thus produced satellite pulses at a delay of $\approx$ 70 fs.

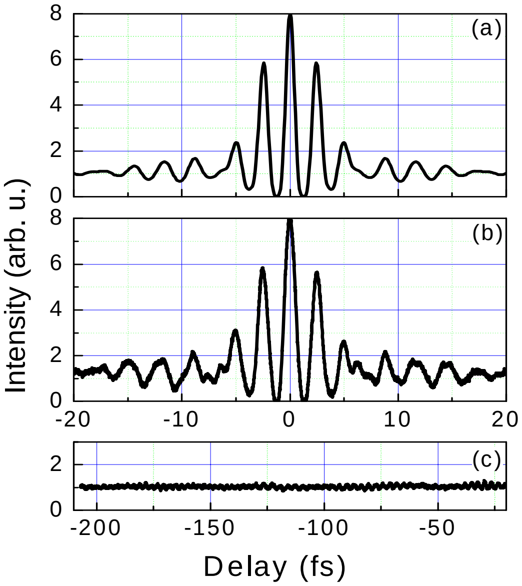

Fig. 5. Second order interferometric autocorrelation calculated from the measured spectrum, corresponding to a bandwidth-limited pulse duration of 4.26 fs (a). Second order interferometric autocorrelation measured with an ultra-broadband dispersion balanced autocorrelator (b). Second order interferometric autocorrelation measured with a long-scan-range autocorrelator (c), as described in the text.

In order to rule out that these satellite pulses produced by the beam splitter hide pre- or post-pulses caused by the dispersive mirrors we have repeated the autocorrelation measurement with a standard autocorrelator (Femtometer, Femtolasers GmbH) employing a 1-mm-thick beam splitter with an AR-coating on the back surface. This autocorrelator is also equipped with a 20-µm crystal which leads to an enhanced dynamic range. With this autocorrelator we have performed long-scan measurements that indicated that no satellite pulses were detectable (Fig. 5c).

6. Conclusions

The analysis of the CM performance in the time domain (achieved by simulating the reflection of a pulse on the multilayer) reveals that the *GD* and *GDD* of the mirror *do not need to be low order polynomial functions of frequency (as believed so far)* in order to support the compression of sub-2-cycle pulses. We have identified the conditions under which the GDD introduced by CMs upon reflection may exhibit extremely large oscillations (of the order of hundreds of fs^2) as a function of the frequency, without significantly impairing on the shape of the reflected pulse. This finding enables the design of single CMs (having air as medium of incidence) with a bandwidth larger than one optical octave and supporting the compression of sub-two-cycle pulses. A mirror compressor designed by means of the time-domain approach and exhibiting peak-to-peak GDD-oscillations > 2000 fs^2 has been successfully employed for the generation of undistorted sub-5-fs, 25-µJ pulses.

Acknowledgments

The authors gratefully acknowledge fruitful discussions with Prof. Ferenc Krausz and Prof. Wolfgang Drexler.

Received 24 October 2005; revised 7 December 2005; accepted 14 December 2005