Pulse compression over a 170-THz bandwidth in the visible by use of only chirped mirrors

M. Zavelani-Rossi, G. Cerullo, and S. De Silvestri

Istituto Nazionale per la Fisica della Materia, Centro di Elettronica Quantistica e Strumentazione Elettronica–Consiglio Nazionale delle Ricerche, Dipartimento di Fisica, Politecnico, I-20133 Milano, Italy

L. Gallmann, N. Matuschek, G. Steinmeyer, and U. Keller

Ultrafast Laser Physics Laboratory, Institute of Quantum Electronics, Swiss Federal Institute of Technology, ETH Zürich Hönggerberg–HPT, CH-8093 Zürich, Switzerland

G. Angelow, V. Scheuer, and T. Tschudi

Institute of Applied Physics, D-64289 Darmstadt, Germany

Received February 12, 2001

We report on double-chirped mirrors with custom-tailored dispersion characteristics over a bandwidth of 170 THz in the visible. The mirrors are used in a prismless compressor for a noncollinear optical parametric amplifier in the visible. The compressed pulses, characterized for the what is believed to be first time by use of the spectral phase interferometry for direct electric field reconstruction technique, display a nearly flat phase from 510 to 710 nm and have a duration of 5.7 fs. © 2001 Optical Society of America

OCIS codes: 320.5520, 190.4970, 320.7100.

Recently, several techniques showed the capability to generate coherent light pulses with bandwidths well in excess of 100 THz, either directly from a laser oscillator[1,2] or by extracavity spectral broadening[3,4] and subsequent broadband amplification.[5–7] The compression of such pulses to a nearly transform-limited duration calls for the development of delay lines with dispersion characteristics that are accurately controlled over ultrabroad bandwidths. Chirped dielectric mirrors[8,9] are a powerful tool for dispersion control; they introduce frequency-dependent group delay (GD) by reflecting different frequency components of the incident radiation at different depths within the multilayer structure. Chirped mirrors are often combined with other dispersive elements, such as prism or grating pairs, for achievement of the desired phase characteristics; these additional elements, however, increase the complexity of the system. Chirped-mirror-only dispersion compensation allows for compactness, reproducibility, and insensitivity to misalignment, which are of great importance in real-world applications.

In this Letter we report on the design and construction of chirped mirrors with custom-tailored dispersion characteristics over a bandwidth of 170 THz in the visible, extending from the blue (510-nm) to the red (710-nm) spectral region. We use these mirrors to compress pulses from a noncollinear optical parametric amplifier (NOPA) to a nearly transform-limited duration of 5.7 fs. We also provide what is believed to be the first full characterization in amplitude and phase of NOPA pulses. Our results are consistent with the limitations of the present dispersion compensation scheme and point out ways to improve its performance.

The NOPA used in this Letter was described elsewhere.[5,10,11] Briefly, the system is pumped by the second harmonic of an amplified Ti:sapphire laser and seeded by the white-light continuum generated in a 1-mm-thick sapphire plate. Parametric gain is achieved in a single pass through a 1-mm-thick β-barium borate (BBO) crystal, cut at $\theta = 32°$, by use of type I phase matching. The amplified pulses have $\approx$2-μJ energy, a 1-kHz repetition rate, peak-to-peak fluctuations of $<7\%$, and TEM_{00} beam quality. To minimize dispersion we use only reflective optics to steer the white light and the amplified beams. With optimum pump–seed angular alignment, the amplified pulse spectra span the whole bandwidth of the noncollinear parametric process in BBO, extending from 500 to 750 nm.[12] For the experiments we suppressed some part of the NOPA spectrum on the low-frequency side by inserting a thin short-pass glass filter into the seed beam.

The GD of the amplified pulses was measured by cross correlation with a 10-nm spectral slice of the NOPA pulse, selected by an interference filter and with $\approx$70-fs FWHM duration. Spectral resolution of the cross-correlation signal in a UV monochromator yields the relative arrival times of different frequency components of the pulse, which sum to a total GD of $\approx$400 fs between the extreme parts of the NOPA spectrum (Fig. 1). Our measurements agree favorably with an independent calculation of the GD of the different optical elements (sapphire plate, BBO crystal, beam splitters, air path).

Based on these measurements, we designed double-chirped mirrors[9,13] (DCMs) to compensate exactly for the dispersion in Fig. 1. These mirrors display high reflectivity, together with small residual oscillations of the group-delay dispersion (GDD), with 8–9-fs^2 amplitude, over the 510–710-nm wavelength range (Fig. 2). The dispersion compensation range is limited by the

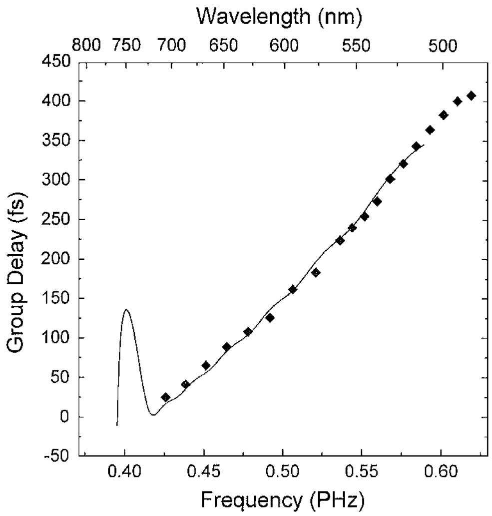

Fig. 1. Diamonds, measured GD of the noncollinear optical parametric amplifier (OPA) pulses before compression; solid curve, opposite of the GD after ten bounces on the DCMs.

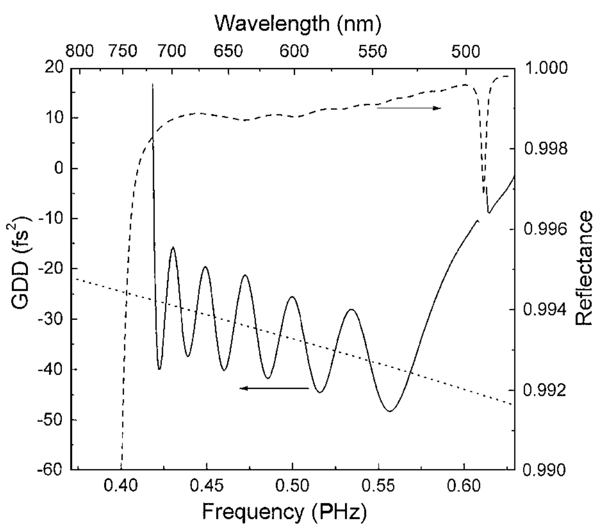

Fig. 2. Reflectivity of the DCM (dashed curve) and the designed (solid curve) and desired (dotted curve) GDD of the DCM.

roll-on of a filter, which we incorporated into the design to suppress the seed wavelength (780 nm). This filter introduces phase distortions at wavelengths longer than 720 nm. The mirrors were manufactured by means of ion-beam sputtering and consist of 30 pairs of alternating SiO_2/TiO_2 layers. We estimate a layer-deposition accuracy of $\approx$0.2 nm rms. As shown in Fig. 1, the resulting GD after ten bounces on the chirped mirrors matches the required GD very accurately over the wavelength range 510–710 nm, with a rms error of 1.8 fs.

To fully characterize the NOPA pulses in amplitude and phase, we use spectral phase interferometry for direct electric field reconstruction (SPIDER).[14] When it is applied to ultrabroadband pulses, SPIDER has several advantages with respect to other pulse characterization techniques. In particular, the accuracy of spectral phase reconstruction is quite insensitive to the phase-matching bandwidth of the upconversion crystal and the spectral responsivity of the detector, since the accuracy depends on only the fringe spacing. In addition, there is a direct, noniterative phase-retrieval algorithm, and there are no moving parts in the apparatus.

The extension of this technique to the visible spectral range with ultrabroadband pulses is not straightforward and requires a careful design of the setup. We employ a novel variant of the SPIDER technique that derives the reference pulse from the infrared pump laser ($\lambda = 780$ nm) rather than from a NOPA. This cross-correlation variant has the advantage of higher signal powers and a more favorable wavelength range (300–380 nm) of the SPIDER trace. Two replicas of the NOPA pulse with a delay $\tau = 271$ fs are generated in a Michelson interferometer with a 100-μm-thick Inconel-coated beam splitter. By use of a 20-μm-thick type II BBO crystal, these replicas are then upconverted with a stretched infrared pulse. A 5-cm-long SF10 glass block (GDD, 8270 fs^2) is employed as a stretcher, which results in a spectral shear of 5.22 THz between the upconverted replicas, obtained when the delay is divided by the GDD. We take advantage of the properties of type II phase matching by orienting the NOPA beam along the ordinary axis, which yields a broader phase-matching bandwidth.[15] The upconverted pulses are detected by a spectrograph with a 1200-groove/mm grating and a 25-μm entrance slit: This setup allows us to resolve spectrally the individual fringes and still cover the full bandwidth of the SPIDER interferogram. To calibrate the apparatus we measure the linear phase term arising from the delay between the second harmonics of the two replica pulses. Since the second harmonic and the SPIDER interferograms do not completely overlap spectrally, we need a very accurate calibration of the spectrometer to extract the linear phase term correctly. This calibration is achieved by measurement of 12 spectral lines of a mercury lamp in the UV spectral region.

Figure 3 shows the SPIDER interferogram of a typical compressed NOPA pulse. The spectral phase reconstructed from the SPIDER trace is plotted in

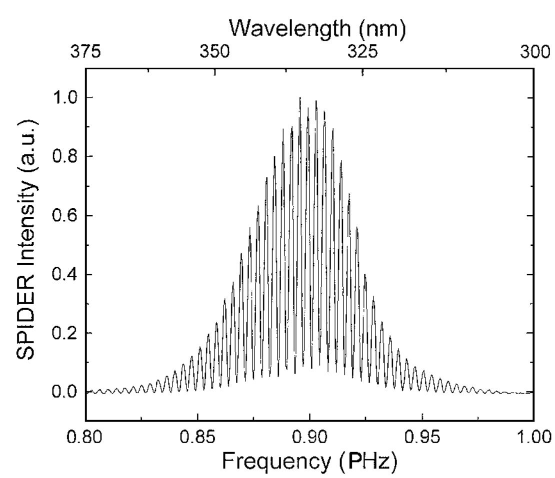

Fig. 3. SPIDER trace of the compressed NOPA pulse.

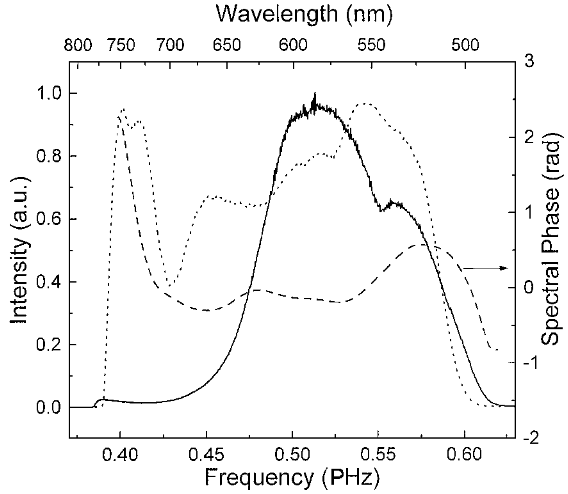

Fig. 4. Spectrum (solid curve) and reconstructed spectral phase (dashed curve) of the compressed NOPA pulse. Dotted curve NOPA spectrum with full-bandwidth operation, corresponding to a transform-limited pulse width of 4.2 fs.

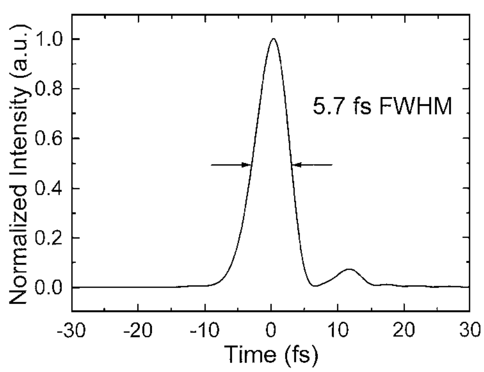

Fig. 5. Reconstructed temporal profile of the compressed OPA pulse.

Fig. 4, together with an independently measured pulse spectrum. The measurements indicate a nearly flat spectral phase in the range from 510 to 710 nm, with negligible residual dispersion oscillations. Phase distortions occur in the red for wavelengths longer than 720 nm and in the blue near 500 nm, in agreement with the GD characteristics of the chirped mirrors. The reconstructed pulse intensity profile is shown in Fig. 5 and has a FWHM of 5.7 fs, to be compared with the transform limit of 5.2 fs. The pulse shape is remarkably clean and nearly free of sidelobes.

Figure 4 depicts an amplified spectrum without any spectral filtering of the white-light seed and shows that there is additional bandwidth available in the NOPA process. The use of a novel mirror technology that employs backside coating[16] of chirped mirrors promises a further increase in bandwidth and should allow for prismless compression of the entire bandwidth of the noncollinear parametric process in BBO.

In conclusion, we have demonstrated the possibility of engineering DCMs with custom-tailored dispersion characteristics over bandwidths of 170 THz in the visible. These mirrors are used to compress pulses from a visible NOPA to a nearly transform-limited duration of 5.7 fs. Such short pulses are easily reproducible on a daily basis without any need for compressor adjustment. The DCM compressor therefore considerably simplifies the use of the NOPA for spectroscopy experiments with extreme time resolution. To our knowledge, the first complete characterization of sub-10-fs NOPA pulses in amplitude and phase has been performed, revealing a nearly satellite-free pulse shape with flat spectral phase over the wavelength range 510–710 nm. The SPIDER method readily detects residual phase distortions introduced by the compressor and points out ways to increase the usable bandwidth further.

Experimental assistance from D. H. Sutter and D. Polli is gratefully acknowledged. This work was supported by the Swiss National Science Foundation. G. Cerullo's e-mail address is giulio.cerullo@polimi.it.

References

1. D. H. Sutter, G. Steinmeyer, L. Gallmann, N. Matuschek, F. Morier-Genoud, U. Keller, V. Scheuer, G. Angelow, and T. Tschudi, Opt. Lett. **24,** 631 (1999).
2. U. Morgner, F. X. Kärtner, S. H. Cho, E. Chen, H. A. Haus, J. G. Fujimoto, E. P. Ippen, V. Scheuer, G. Angelow, and T. Tschudi, Opt. Lett. **24,** 411 920 (1999).
3. A. Baltuska, Z. Wei, M. S. Pshenichnikov, and D. Wiersma, Opt. Lett. **22,** 102 (1997).
4. M. Nisoli, S. De Silvestri, O. Svelto, R. Szipöcz, K. Ferencz, Ch. Spielmann, S. Sartania, and F. Krausz, Opt. Lett. **22,** 252 (1997).
5. G. Cerullo, M. Nisoli, S. Stagira, and S. De Silvestri, Opt. Lett. **23,** 1283 (1998).
6. A. Shirakawa, I. Sakane, and T. Kobayashi, Opt. Lett. **23,** 1292 (1998).
7. A. Shirakawa, I. Sakane, M. Takasaka, and T. Kobayashi, Appl. Phys. Lett. **74,** 2268 (1999).
8. R. Szipöcs, K. Ferencz, C. Spielmann, and F. Krausz, Opt. Lett. **19,** 201 (1994).
9. F. X. Kärtner, N. Matuschek, T. Schibli, U. Keller, H. A. Haus, C. Heine, R. Morf, V. Scheuer, M. Tilsch, and T. Tschudi, Opt. Lett. **22,** 831 (1997).
10. G. Cerullo, M. Nisoli, and S. De Silvestri, Appl. Phys. Lett. **71,** 3616 (1997).
11. G. Cerullo, M. Nisoli, S. Stagira, S. De Silvestri, G. Tempea, F. Krausz, and K. Ferencz, Opt. Lett. **24,** 1529 (1999).
12. G. M. Gale, M. Cavallari, T. J. Driscoll, and F. Hache, Opt. Lett. **20,** 1562 (1995).
13. N. Matuschek, F. X. Kärtner, and U. Keller, IEEE J. Quantum Electron. **35,** 129 (1999).
14. C. Iaconis and I. A. Walmsley, Opt. Lett. **23,** 792 (1998).
15. L. Gallmann, D. H. Sutter, N. Matuschek, G. Steinmeyer, U. Keller, C. Iaconis, and I. A. Walmsley, Opt. Lett. **24,** 1314 (1999).
16. N. Matuschek, L. Gallmann, D. H. Sutter, G. Steinmeyer, and U. Keller, Appl. Phys. B **71,** 509 (2000).