1 November 1995

OPTICS COMMUNICATIONS

ELSEVIER

Optics Communications 120 (1995) 321–324

Compact, high-throughput expansion-compression scheme for chirped pulse amplification in the 10 fs range

Ch. Spielmann [a], M. Lenzner [a], F. Krausz [a], R. Szipöcs [b]

[a] *Abteilung Quantenelektronik, Technische Universität Wien, Gusshausssstrasse 27, A-1040 Wien, Austria*

[b] *Research Institut for Solid State Physics, H-1525 Budapest, POB 49, Hungary*

Received 3 July 1995

Abstract

A novel pulse stretching-compression system suitable for kHz-rate chirped-pulse amplification of ≈10 fs pulses in Ti:sapphire systems is demonstrated. The material dispersion of the system components used for pulse selection and isolation broadens the wide-band seed pulses by a factor of ≈300, allowing amplification up to the submillijoule energy range. The compressor consists of a pair of prisms and newly-developed chirped multilayer dielectric mirrors for compensating high order dispersion. Using this simple scheme a recompression of unamplified pulses down to 15 fs with a throughput as high as 80% is demonstrated.

Recent advances in ultrashort pulse generation have led the generation of sub-10 fs pulses directly from laser oscillators [1,2]. These systems open up new prospects for ultrafast spectroscopy. Nevertheless the pulse energy of a few nJ available from these oscillators is often too low for nonlinear optical applications. Recently 13 fs, 60 nJ pulse generation was demonstrated from a cavity-dumped Ti:sapphire laser [3]. To boost the pulse energy up to or beyond the microjoule level external amplification is needed. The concept of chirped pulse amplification (CPA) [4] allows simultaneously for efficient energy extraction and the avoidance of nonlinear effects in solid state amplifiers. The amplification of sub-50 fs pulses calls for CPA systems compensated for high-order dispersion. To this end, a number of pulse expansion-compression schemes have been proposed and demonstrated [5–10]. Terawatt-scale low-repetition-rate CPA systems rely on pulse stretching up to ≈100 ps or more, and hence on one of the previously proposed sophisticated and lossy grating-based stretcher-compressor systems [11,12]. By contrast, careful design of gigawatt-scale kHz-rate systems allows for the avoidance of excessive nonlinearities with stretched pulse durations of just a few picoseconds [13]. In this letter we demonstrate a simple, high-throughput pulse expansion-compression scheme that is ideally suited for the implementation of the CPA concept in the amplification of ≈10 fs pulses up to multigigawatt power levels.

One expects an optimized CPA system to meet the following requirements: (i) the overall system bandwidth is limited by that of the amplifier medium, and (ii) the dispersion characteristics of the stretcher, amplifier and compressor are matched. The latter requirement can be more precisely formulated after expanding the group delay τ of the whole system, around the center frequency ω_0 in a Taylor series:

$$\tau(\omega) = \partial\phi(\omega)/\partial\omega = \phi'(\omega_0) + \phi''(\omega - \omega_0) + \tfrac{1}{2}\phi'''(\omega - \omega_0)^2 + \tfrac{1}{6}\phi''''(\omega - \omega_0)^3 + \ldots, \quad (1)$$

SSDI 0030-4018(95)00494-7

where $\phi(\omega)$ stands for the phase retardation, $\phi'(\omega_0)$ is the group delay at the center frequency, and the higher-order derivatives of ϕ represent the group-delay dispersion (GDD), third-order dispersion (TOD), fourth order dispersion (FOD), etc., respectively. For distortion-free amplification of gain-bandwidth-limited pulses the group delay $\tau(\omega)$ must be approximately constant over the gain bandwidth. In practical broadband systems (such as Ti:sapphire) this condition can be fullfilled if ϕ'' and ϕ''' can be adjusted to zero and higher-order dispersion contributions can be kept at a low level. Previously this was achieved by combining diffraction gratings with other dispersive components.

By contrast, we have developed a kHz-repetition-rate Ti:sapphire amplifier in which exclusively low-loss dispersive elements such as prisms, dielectric mirrors, and transparent optical materials have been used for dispersion control. The ≈10 fs pulses produced by our Ti:sapphire laser traverse a KD*P Pockels cell, a Berek compensator (New Focus), and a broadband Faraday isolator before entering the amplifier. The multipass amplifier contains a 7 mm long highly-doped Ti:sapphire crystal. Employing a short highly-doped gain medium minimizes the nonlinear interaction length in the crystal. This is a prerequisite for the amplification of moderately stretched pulses. The material dispersion of these components (incl. 4 passes through the gain medium) adds up to $\phi'' \approx 8700$ fs^2 and $\phi''' \approx 6500$ fs^3. This dispersion is sufficient to broaden a 10 fs pulse to ≈3.2 ps. Since the overall material dispersion is dominated by that of the isolator and Pockels cell, the stretched pulse duration is comparable at the input and output of the amplifier. Owing to the short gain medium and high single-pass amplification achievable with this system [13], the B-integral can be kept below 0.2 for amplified pulse energies up to 0.1 mJ in spite of the relatively short stretched pulse duration.

One of the major benefit of a moderate stretching is the comparatively low GDD to be compensated for in the compressor. As a result, the lossy gratings previously used can be replaced by a low-loss Brewster-angled prism pair, as shown in Fig. 1. As an additional advantage, in contrast with gratings, prism pairs introduce a TOD with opposite sign with respect to the (positive) material TOD. However, for a center wavelength around 800 nm the negative TOD of prism pairs tends to overcompensate the TOD [14,15] of optical materials if the GDD is equal to zero. To minimize the residual negative TOD a prism pair made of a low dispersive material must be used. We have opted for FK5 (Schott) prisms because they exhibit dispersion characteristics similar to that of fused silica, while being less expensive, especially with large apertures.

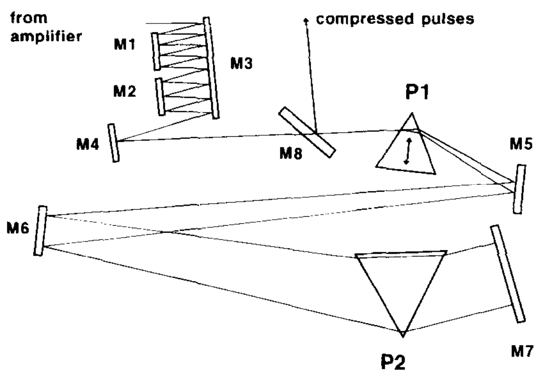

Fig. 1. Setup of the compressor. P1 and P2 are low dispersive prisms made of FK5, M1-M6 chirped mirrors exhibiting a positve TOD, and M7,M8 standard quarterwave mirrors.

Compensation of the material GDD of the amplifier system (and the prisms themselves) calls for a prism separation of 5.4 m in our case. The dimensions of this compressor can be reduced by using folding mirrors between the prisms. The double-passed prism compressor and the material dispersion yield a residual TOD and FOD of $\phi''' = -4800$ fs^3, and $\phi'''' \approx -30000$ fs^4. These values would cause a broadening of a 10 fs Gaussian-pulse to ≈ 23 fs and ≈ 11 fs pulse, respectively. Hence we may conclude that recompression of the seed pulses is most severely affected by the residual TOD of the system.

Fortunately, each of the quarterwave multilayer dielectric mirrors used for steering and focusing the beam introduces a small but finite *positive* TOD, which, in total, reduces the residual TOD by some 30%. In order to eliminate this residual TOD, specifically-designed chirped multilayer mirrors exhibiting a negative GDD and positive TOD have been developed. In contrast with previous designs, which were optimized for minimum high-order dispersion [16], the high-order dispersion is tailored here for controlling TOD in the amplifier. [17] The reflectivity and GDD of the novel chirped mirrors are shown in Fig. 2. A polynomial fit to the calculated disper-

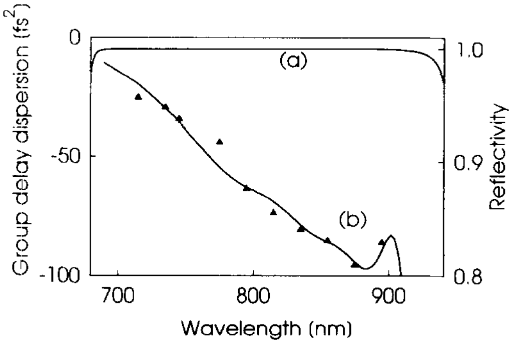

Fig. 2. (a) Reflectivity and (b) group delay as a function of the wavelength for the TOD compensator. The triangles represent measured data obtained with a white-light interferometer.

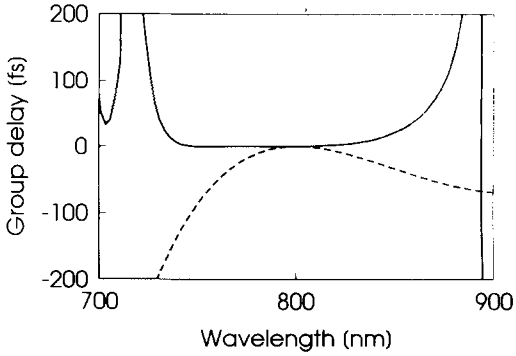

Fig. 3. Group delay versus wavelength for dispersion control provided by the prisms only (dashed line) and for the whole system including the quarterwave steering and focusing mirrors as well as the chirped TOD compensators.

sion curve yields a GDD of -57 fs^2 and a TOD of 150 fs^3 at 800 nm. These chirped TOD-compensating mirrors provide dispersion control over significantly broader bandwidths than previously demonstrated with thin-film devices [18,19]. Supplementing the prism compressor with the chirped mirrors results in a reduction of the negative TOD in two different ways: first, the prism separation can be reduced due to the negative GDD of the mirrors and secondly, the residual TOD is directly lowered by the positive TOD of the chirped mirrors.

The compressor can now be optimized by adjusting the prism separation, prism insertion, and number of bounces on the TOD mirrors so that the expansion coefficients in (1) are cancelled. Even though there are three freely adjustable parameters the overall system dispersion can be eliminated only up to third order because of the lack of a dispersive element capable of compensating the negative FOD of the prism pair. With a prism separation of 5.4 m, total (double-pass) prism insertion of 12 cm and 20 bounces on the chirped mirrors both $\phi''(\omega_0)$ and $\phi'''(\omega_0)$ can be made equal to zero. The residual FOD of the system is estimated as $\phi'''' \approx -3 \times 10^4$ fs^4. Fig. 3 plots the group delay (GD) versus wavelength for dispersion control provided by the prisms only (dashed line) and for the whole system including the quarterwave steering and focusing mirrors as well as the chirped TOD compensators. TOD compensation results in a significant extension of the wavelength range over which the GD is nearly constant. The rapid increase in the GD below 740 nm and above 870 nm relates to the edges of the high reflectivity ranges of the quarter-

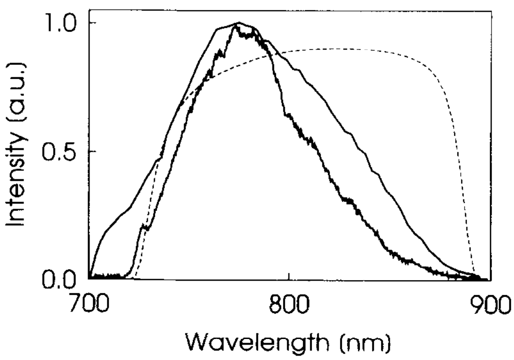

Fig. 4. The dashed line indicates the overall transmittivity of the system, which narrows the ≈100 nm broad seed spectrum (upper solid line) to ≈70 nm (lower solid line).

wave mirrors employed. Note that in this wavelength regions the Taylor expansion up to the fourth order is no longer an aprropriate description of the actual GD.

The expansion-compression system has been tested using 100 nm bandwidth pulses ($\tau \approx 10$ fs) delivered by a MDC self-modelocked Ti:sapphire laser. At a center wavelength of about 780 nm such broad modelocked spectral widths can currently only be produced by the MDC Ti:sapphire laser. [1] An incomplete overlap of the high-reflectivity ranges of the focusing and steering mirrors and the isolator transmittivity centered at 820 nm results in an overall bandwidth of the "cold" amplifier of ≈ 150 nm (see dashed line in Fig. 4). The finite system bandwidth reduces the width of the transmitted spectrum to ≈70 nm (Fig. 4). Narrowing of the spectrum on the long-wavelength side presumably originates from some residual birefringence

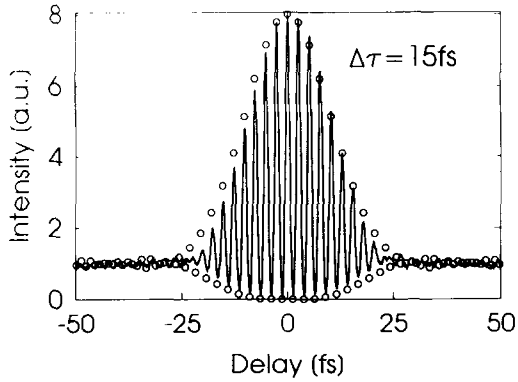

Fig. 5. Measured fringe-resolved autocorrelation of the recompressed pulses (solid line), and best fit with a FOD parameter of -2×10^4 fs^4 (circles).

of the pulse selection–isolation system, which was not considered in the calculation of the dashed line in Fig. 4. The fringe-resolved autocorrelation (FRAC) trace of the pulses transmitted through the whole system is shown in Fig. 5. The pulse duration has been evaluated by calculating the FRAC from the transmitted spectrum with a given FOD allowed. The best agreement between the calculated and the measured FRAC trace was achieved with a FOD $\phi'''' = -2\times10^4$ fs^4, yielding a recompressed pulse duration of 15 fs. A comparison with the calculated transform-limited pulse duration of 14.3 fs indicates that the effect of FOD is marginal.

The overall transmission efficiency of the whole system has been measured to be ≈35%, with a compressor throughput exceeding 80%. The first of these numbers could be increased well beyond 50% by replacing the 2 mm aperture transverse Pockels cell by a large-aperture device. The high throughput is extremely important if the shortest possible pulses are to be amplified. This is because losses can only be compensated by excess gain, which reduces the effective bandwidth of the amplifier (due to gain narrowing). With the amplifier pumped, preliminary experiments yielded amplified pulses with a duration of 17–18 fs and an energy of 0.1 mJ at a repetition rate of 1 kHz. [13] These are the first sub-20 fs pulses amplified to multigigawatt power levels. Nevertheless, the potential of the presented scheme is not fully exploited yet. Some simple improvements (replacing the quarterwave steering and focusing optics by broad-band chirped mirrors and using a shorter gain medium for reducing nonlinear effects) should permit the generation of sub-15 fs pulses in the sub-mJ energy range at kHz repetition rates in the near future. This simply, powerful, and user-friendly implementation of the CPA concept is expected to rapidly proliferate in laboratories in which ultrafast spectroscopy is to be performed at the cutting edge of optical time resolution.

We gratefully acknowledge A.J. Schmidt and N. Kroo for their stimulating support and K. Ferencz for manufacturing the chirped mirrors. This work was supported by the FWF Österreich, grants P 9710 and P 10409, the ÖNB, grants 4915 and 5335, the Hungarian Science Foundation grant T 7376, and the WTZ-O-U project A 17. M. Lenzner acknowledges support from the Deutsche Forschungsgemeinschaft.

References

[1] A. Stingl, M. Lenzner, Ch. Spielmann, F. Krausz and R. Szipöcs, Optics Lett. 20 (1995). (1995).
[2] J. Zhou, G. Taft, C.P. Huang, M.M. Murnane, H.C. Kapteyn and I. Christov, Optics Lett. 19 (1994) 1149.
[3] M.S. Pshenichnikov, W.P. de Boeij and D.A. Wiersma, Optics Lett. 19 (1994) 572.
[4] D. Strickland and G. Mourou, Optics Comm. 56 (1985) 219.
[5] B.E. Lemoff and C.P.J. Barty, Optics Lett. 18 (1993) 1651.
[6] J.V. Rudd, G. Korn, S. Kane, J. Squier, G. Mourou and P. Bado, Optics Lett. 18 (1993) 2044.
[7] J.K. Rhee, T.S. Sosnowski, T.B. Norris, J.A. Arns and W.S. Colburn,Optics Lett. 19 (1994) 1550.
[8] K. Wynne, G.D. Reid and R.M. Hochstrasser, Optics Lett. 19 (1994) 895.
[9] T. Joo, Y. Jia and G.R. Flemming, Optics Lett. 20 (1995) 389.
[10] A. Sullivan and W.E. White, Optics Lett. 20 (1995) 192.
[11] C.P.J. Barty, C.L. Gordon and B.E. Lemoff, Optics Lett. 19 (1994) 1442.
[12] J. Zhou, C.P. Huang, M.M. Murnane and H.C. Kapteyn, Optics Lett. 20 (1995) 64.
[13] M. Lenzner, Ch. Spielmann, E. Wintner, F. Krausz and A.J. Schmidt, Optics Lett. 20 (1995). (1995).
[14] Ch. Spielmann, P.F. Curley, T. Brabec, E. Wintner and F. Krausz, Electron. Lett. 28 (1992) 1532.
[15] B.E. Lemoff and C.P.J. Barty, Optics Lett. 18 (1993) 57.
[16] R. Szipöcs, K. Ferencz, Ch. Spielmann and F. Krausz, Optics Lett. 19 (1994) 201.
[17] R. Szipöcs, A. Stingl, Ch. Spielmann and F. Krausz, Proc. 1995 Photonics West, Paper 2377-02 (1995).
[18] K.D. Li, W.H. Knox and N.M. Pearson, Optics Lett. 14 (1989) 450.
[19] J.M. Jacobson, K. Naganuma, H.A. Haus, J.G. Fujimoto and A.G. Jacobson, Optics Lett. 17 (1992) 1608.