Dispersion control in a 100 kHz repetition rate 35-fs laser system

F. Lindner[a], M.G. Schätzel*[a], F. Grasbon[a], A. Dreischuh[b], G.G. Paulus[c] and H. Walther[a,c]

[a]MPI für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany
[b]Sofia University, 5, James Bourchier Blvd., 1164 Sofia, Bulgaria
[c]Ludwig-Maximiliams-Universität München, Am Coulombwall 1, 8578 Garching, Germany

ABSTRACT

We present a 100 kHz femtosecond amplifier system delivering pulses with a duration of 35 fs and an energy of 7 μJ at 800 nm. The system does not include a stretcher, since the large amount of dispersion accumulated during the amplification process is sufficient to prevent self-focusing. Compensation in all orders is achieved through a combination of a special prism compressor, chirped mirrors, and a liquid-crystal modulator.

Keywords: 100 kHz repetition rate, dispersion control, fs laser

1. INTRODUCTION

Femtosecond technology based on Ti:sapphire crystals opened the way to generating intense optical fields using reliable tabletop laser systems. Lasers based on this technology are used to explore elementary processes in many fields of physics, chemistry, and photobiology.[1] The energies of the laser pulses generated directly from various types of Ti:sapphire oscillators are suitable for specific applications. Many others require, however, higher pulse energies. The problem of achieving the highest energies without damaging the crystal is usually solved by stretching the input pulse before amplification and recompressing it afterwards. This technique is referred to as chirped-pulse amplification (CPA).[2]

At 5 kHz 30 fs pulses can be obtained in a single-stage regenerative amplifier system showing saturation after about 20 round trips.[3] Furthermore, the highest repetition rates (>10 kHz) are only possible with continous wave (cw) pumping, which implies that multipass amplifiers cannot be used. In the case of cw-pumping a Q-switch in the amplifier cavity is needed to suppress amplified spontaneous emission (ASE) and achieve optimal amplification. The upper limit of the repetition rate (~250 kHz) is then only imposed by the radiative lifetime of the active medium Ti:sapphire (~3 μs). At this repetition rate pulse energies of 3 μJ at a pulse duration of 60 fs can be achieved with a commercially available system (RegA 9050, Coherent).[4]

The tabletop system presented here can achieve an intensity of more than $5 \cdot 10^{14}$ W/cm^2 (f-number 8) at a repetition rate of 100 kHz. Conventional chirped-pulse-amplification is not used, i.e. the laser pulses are not stretched in a dedicated stage before amplification. Nevertheless, the pulses have to be compressed due to the large amount of dispersion accumulated during the amplification process. Compensation of dispersion in many orders is possible through an efficient combination of several optical techniques: a special prism compressor, chirped mirrors, and a liquid-crystal phase modulator. This allows the amplified pulses to be shortened down to 35 fs, with an energy exceeding 7 μJ.

2. DESCRIPTION OF THE LASER SYSTEM

The laser system consists of a Ti:sapphire oscillator, a spatial light modulator (SLM) in a 4f configuration, a regenerative amplifier, and a prism compressor.

* e-mail: iis@mpq.mpg.de, telephone: ++49 (0)89 32905 294

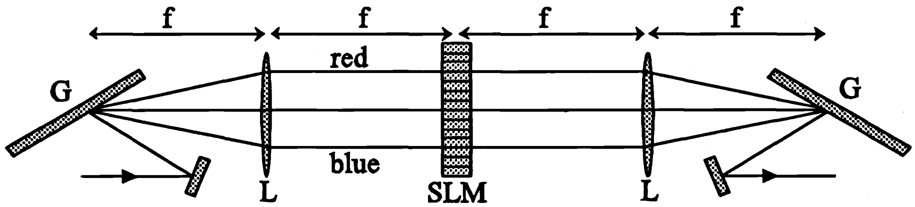


Figure 1. 4f setup with achromatic spherical lenses (L) and spatial light modulator (SLM) in the Fourier plane. The diffraction gratings (G) are nearly at the Littrow angle.

2.1. The Ti:sapphire oscillator

A standard Kerr-lens mode-locked oscillator generates the pulses to be amplified. The mean output power is 200 mW at a repetition rate of 78 MHz. Group velocity dispersion (GVD) control is achieved through a prism pair[5] and three chirped mirrors.[6,7] This leads to a spectrum exceeding 35 nm (Fig. 2) and a pulse duration of about 25 fs. For convenience and increased stability, the direction and position of the laser beam is stabilized with a set of quadrant diodes and piezo-driven mirrors directly after the cavity.

2.2. The 4f setup and phase modulator

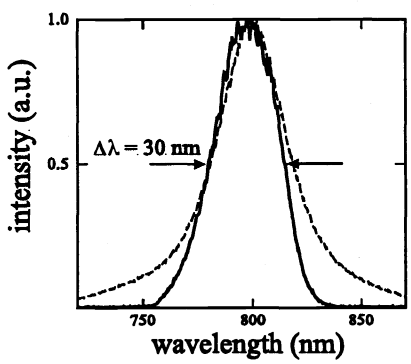
While the lion's share of dispersion is compensated after amplification and will be discussed below, we precompensate the rest with a phase modulator in a 4f setup (Fig. 1). It consists of two Littrow-gratings (1200 lines/mm) and identical achromatic lenses (f = 80 mm, Halle, Berlin) in a symmetric zero-dispersion configuration. A liquid-crystal phase modulator (SLM 128-CRI) is placed in the Fourier plane,[8,9] where optimal spatial separation of the different wavelengths occurs. The modulator itself consists of an array of $N = 128$ pixels which can independently influence the phase of the respective spectral component by means of an applied voltage. The width of each pixel is 97 μm, and their mutual separation 3 μm. The SLM is controlled via a GPIB interface and programmed by an evolutionary algorithm.[10]

2.3. The regenerative amplifier

The oscillator pulses seed a commercial regenerative amplifier (RegA 9050, Coherent; Fig. 3). The Q-switched cavity of the amplifier is cw-pumped by 17 W of an Ar^+ ion laser (Sabre, Coherent). The design allows repetition rates of up to 250 kHz. However, due to the higher pulse energy, a repetition rate of 100 kHz is favored in this case. The resonator was modified by adding a variable number of reflections on specially designed chirped mirrors, which introduce additional third-order dispersion (TOD). The number of round trips is kept as low as possible in order to reduce the total accumulated dispersion. After 18 round trips the amplified pulses are ejected with a pulse energy exceeding 8 μJ, and a spectral width of approximately 30 nm (Fig. 2).

2.4. The prism compressor

The huge amount of dispersion accumulated in the amplifier stage has to be compensated in order to obtain short pulse durations. This is done through a prism compressor (Fig. 4). The most reasonable choice of design is a Proctor-Wise double prism pair configuration.[11] This reduces the length roughly by a factor of 4 relative to a standard Fork compressor[5] with the same type of glass. The choice of the special glass (S LAL 59, OHARA) is discussed in the following section. The prism separation, adjustable with a moveable folding mirror set, is determined by compensating second-order dispersion (SOD). To reduce the prism distance the compressor is passed twice. The resulting distance between the prism pairs is 2.25 m. The total transmittance of the compressor is almost 90%. Integrated in the setup is also a set of piezo-driven mirrors controlled by CCD-cameras and a PC, to compensate for long-term drifts of the beam.



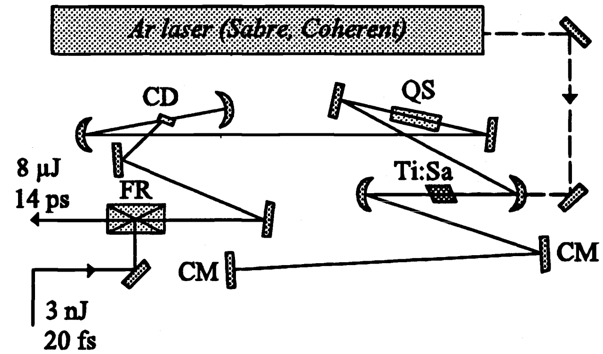
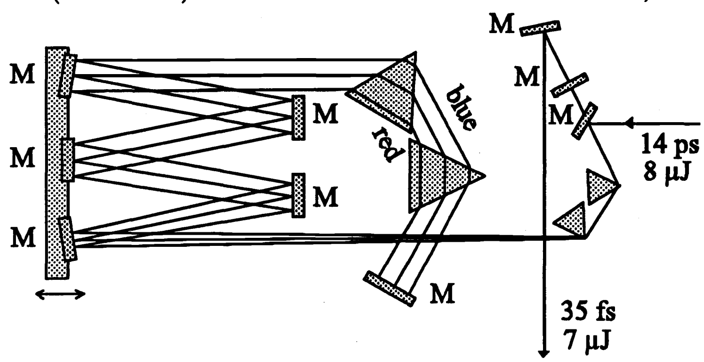


Figure 2. Power spectra of the outputs of the regenerative amplifier (solid line) and the oscillator (dashed line).

Figure 3. Scheme of the regenerative amplifier: Ti:Sa - Ti:sapphire crystal, CM - TOD chirped mirrors, CD - cavity dumper, QS - Q-switch, FR - Faraday isolator.



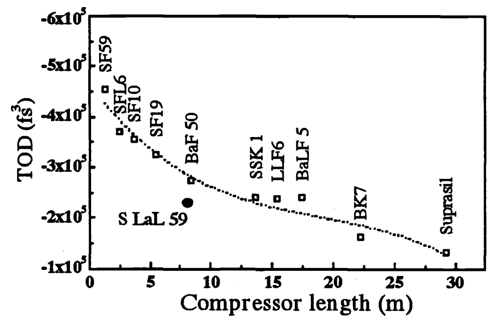


Figure 4. Prism compressor of Proctor-Wise type. Prism material - S LAL 59 (OHARA); M - broadband dielectric mirrors, three of them mounted on a common translation stage.

Figure 5. Calculated third-order dispersion and compressor length needed to compensate for the second-order dispersion introduced by the amplifier, for different types of glasses.

3. DISPERSION COMPENSATION

Contrary to most femtosecond amplifier systems with a dedicated stretching stage, our laser simply relies on the fact that sufficient broadening of the pulses naturally occurs due to the accumulated dispersion during the amplification process. The Q-switch (42 mm SiO_2), the cavity dumper (3 mm SiO_2), and the Ti:sapphire crystal (20 mm) induce a dispersion approximately equivalent to 15 cm of fused silica per round trip. This large amount of dispersion is peculiar to our system, where the high repetition rate prevents the use of a pulsed pump laser and, therefore, requires a Q-switch to reach the desired inversion in the gain medium. After 18 round trips a large amount of positive second-order dispersion (SOD = +100 000 fs^2) is produced. The positive third-order dispersion (TOD = +76 000 fs^3) also affects the temporal pulse shape, while fourth-order dispersion is small (FOD $\approx$ -28 000 fs^4). The pulse duration already increases to 700 fs after the first round trip and to almost 14 ps before cavity dumping. Considering the pulse energies and the cavity design, the nonlinear phase – represented by the B integral – is well below its critical value.[2]

The absence of a dedicated stretcher stage is a great advantage with respect to the complexity of the system. However, clever alignment of the grating stretcher and compressor in principle allows compensation of not only second-order but also higher-order dispersion.[12] In this sense, using a prism compressor without stretcher reduces the number of parameters to adjust the dispersion.

Despite this and the large dimension required, the choice of a prism compressor can be motivated as follows. First, the efficiency (>85%) is higher than that of the widely used grating compressor (~60%). Second, the TOD of the prism compressor is negative, while in conventional grating compressors it is positive (Table 1): while the grating compressor increases the TOD of the amplifier, the prism compressor balances it.[12]

The residual TOD can be roughly corrected by inserting a suitable number of high-reflectivity TOD mirrors (Femtolasers, R = 99%) in the amplifier cavity. Considering the losses they introduce, the number of reflections on these intracavity chirped mirrors should, however, be kept as low as possible. Moreover, these mirrors also introduce some residual SOD that has to be considered for balancing the dispersion.

Both the residual TOD and the length of the compressor are determined by the prism glass. In Fig. 5 we show for some glasses the length needed to compensate for the given SOD of the amplifier, and the corresponding negative TOD induced by the compressor. Note that all glasses overcompensate the positive TOD of the amplifier (+76 000 fs^3).

A good compromise of length of the compressor and residual TOD is achieved by using the special glass S LAL 59 (OHARA). The length of the compressor is 8 m (as short as for BaF50) and the residual TOD is -154 000 fs^3 (as low as for LLF6). Since each passage on a TOD mirror introduces approximately +1 800 fs^3, 85 reflections would be necessary to compensate for the TOD. Considering also the positive SOD of the chirped mirrors (+130 fs^2), a balance is provided by using three such mirrors in the amplifier (5 reflections per round trip, giving 90 reflections) and some additional ones outside the cavity (10 reflections) for fine adjustment. The corresponding total length of the compressor is 9.15 m.

Table 2 shows the balance of the first three orders of dispersion in the laser system. It should be noted that these calculations should not be taken too literally. In fact, the indicated dispersion of the TOD mirrors is a theoretical estimate whose reliability is not very high, especially for the fourth-order dispersion (FOD). Moreover, these values are dependent on the angle of incidence, which can be chosen in our system since some TOD mirrors are used as folding mirrors.

Figure 6 shows the corresponding noncollinear autocorrelation. Taking the Fourier transform of the spectrum gives a bandwidth limit of 32 fs and indicates that the assumption of a gaussian shape is very good. The pulse duration can then be estimated to 60 fs, far above the bandwidth limit. Moreover, the presence of a huge pedestal indicates that the pulse energy is actually dispersed over a longer time, due to the uncompensated higher orders of dispersion.

The liquid-crystal phase modulator is used for fine precompensation of these higher orders. The overall accepted bandwidth of the modulator is 120 nm, well above that of the incident pulse, and the resolution is approximately 0.95 nm/pixel. Careful alignment guarantees a symmetric setup, with the central wavelength passing in the center of the array.

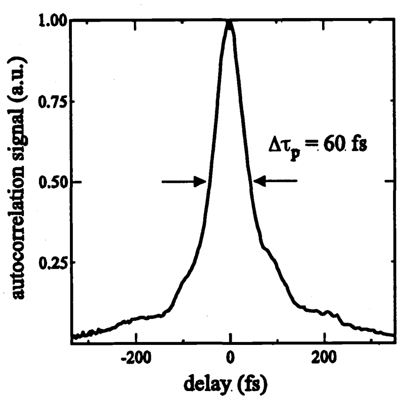
According to the Nyquist theorem, the phase difference between two adjacent pixels must not exceed π.[13] For a purely quadratic, cubic or quartic phase distribution, this implies – in our case – a limitation of $5 \cdot 10^3$ fs^2, $5 \cdot 10^4$ fs^3, and $8 \cdot 10^5$ fs^4 respectively for the maximum SOD, TOD, and FOD applicable. Taking into account the simultaneous presence of terms of different sign in the phase expansion, even greater values can be achieved. These limitations clearly indicate that the use of the SLM is appropriate to compensate for higher orders of dispersion, provided that the main compensation is realized elsewhere.

Table 1. Signs of the second-order (SOD), third-order (TOD) and fourth-order (FOD) dispersion for an optical material, a grating compressor, and a prism compressor.

	SOD	TOD	FOD
Material	+	+	±
Grating	−	+	−
Prism	−	−	−

Table 2. The dispersion balance in the laser system, without using the SLM: second-order (SOD), third-order (TOD) and fourth-order (FOD) dispersion.

Dispersion	SOD (fs^2)	TOD (fs^3)	FOD (fs^4)
RegA (per RT)	+5 560	+4 240	-1 550
Prism compressor (per mm)	-12.36	-28.36	-55.23
TOD mirror / reflection	+130	+1 800	$+10^4$ (?)
RegA (18 RT)	+100 000	+76 000	-28 000
Prism compressor (L=9.15 m)	-113 000	-259 000	-505 000
TOD mirrors (100 reflections)	+13 000	+180 000	$+10^6$ (?)
Residual dispersion ≈	0	-3 000	500 000 (?)



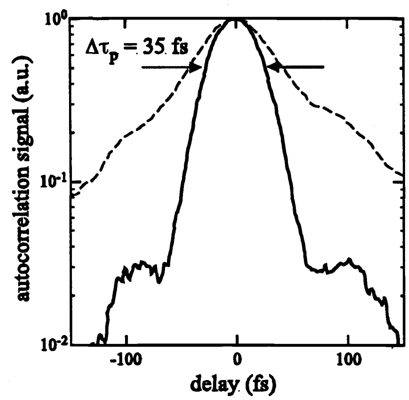


Figure 6. Noncollinear autocorrelation of the amplified and compressed pulses without the SLM in operation. A gaussian shape is assumed for the determination of the pulse durations.

Figure 7. Noncollinear autocorrelation of the amplified and compressed pulses with the SLM in operation (solid line). For comparison, the trace without use of the SLM is also shown (dashed line).

The phase distribution applied is chosen by adjusting the voltage values in a feedback loop. We focus the beam in a nonlinear crystal (BBO, 20 μm) and record the resulting second harmonic (SH) as a feedback signal. Adjustement of the voltage of each pixel for maximum SH represents an optimization problem which is solved with an evolutionary algorithm.[10,13,14] Convergence of the procedure (Fig. 8) is rather fast (typically 2-3 minutes) if advantage is taken of the a-priori physical knowledge such as the expected sign and extent of the dispersion that has to be applied.

Use of the SLM has also afforded the possibility of reducing the number of TOD mirrors used in the system. This is highly desirable in view of the losses they introduce. In the final configuration there are only two TOD mirrors in the amplifier (three reflections per round trip, cf. Fig. 3). The typical phase function retrieved by the algorithm is also shown in Fig. 9. This distribution compensates for the higher orders and, as expected, is dominated by a positive third-order dispersion term.

Figure 7 shows the noncollinear autocorrelation of the amplified and compressed pulses with the SLM in operation. The significant reduction of the pedestal confirms that higher order dispersion is almost completely removed by the liquid crystal phase modulator. The pulse duration is 35 fs, slightly above the bandwidth limit, probably due to the discrete nature of the phase distribution of the SLM.

If a feedback directly related to the peak intensity is available from the experiment (e.g. integral rates in an ionization experiment), it is possible to make the pulse shortest in the experimental environment itself. This makes the system very flexible if optical elements (waveplates, polarizers, ...) are added. Furthermore, it is in principle possible to use differential rates as feedback, allowing the evolutionary algorithm to selectively optimize different physical processes.[15,16]

4. CONCLUSION

We have reported a 100 kHz Ti:sapphire laser system delivering pulses with energies of 7 μJ and durations of 35 fs. Due to the high repetition rate, cw pumping and Q-switching of the regenerative amplifier are needed and a much larger amount of dispersion than in typical kHz lasers is accumulated. The corresponding broadening of the pulse permits amplification without stretching. Pulse compression is achieved through a particular combination of a prism compressor, chirped mirrors, and a liquid-crystal phase modulator.

This procedure is precise and stable, allowing nearly transform-limited output pulses to be obtained routinely. The high peak intensities of the pulses and the high repetition rate make this system a valuable tool for investigating highly-nonlinear phenomena, such as high-harmonic generation, above-threshold ionization,[17,18] and, in

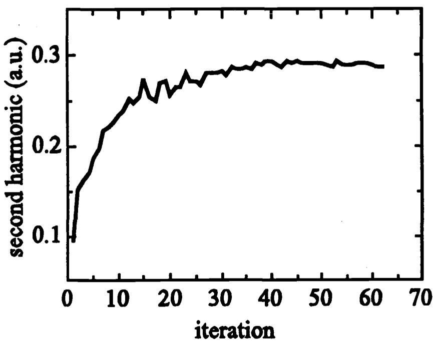


Figure 8. Convergence of the second-harmonic signal while running the evolutionary algorithm.

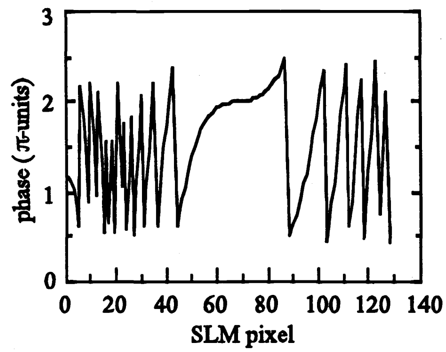


Figure 9. Typical phase distribution applied by the SLM.

particular, coincidence techniques requiring very low probability of an event per laser shot (e.g. COLTRIMS[19]). With respect to these applications, the great advantage of using the SLM is the possibility of obtaining the shortest pulses in the interaction region.

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