Dispersion Control in a 100-kHz-Repetition-Rate 35-fs Ti : Sapphire Regenerative Amplifier System

F. Lindner, G. G. Paulus, F. Grasbon, A. Dreischuh, and H. Walther

***Abstract*—This paper presents a 100-kHz femtosecond amplifier system delivering pulses with a duration of 35 fs and an energy of 7 μJ. 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 approximately all orders is achieved through a combination of a prism compressor, chirped mirrors, and a liquid-crystal modulator, allowing the amplified pulses to be shortened to nearly the bandwidth limit.**

***Index Terms*—Dispersion control, femtosecond laser, high repetition rate, pulse shaping, regenerative amplifier, ultrafast optics.**

I. 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], [21].

There are two basic amplifier designs. In a multipass amplifier, the beam passes a few times through a gain medium pumped with a pulsed source. In a regenerative amplifier, on the other hand, the pulse is injected into a resonator (pumped either continuous wave (CW) or pulsed) and is ejected after many round trips, when amplification has saturated.

The multipass configuration has two main advantages [3]. First, the absence of a cavity reduces the buildup of amplified spontaneous emission (ASE). Second, due to the high gain (in the strongly pumped medium), fewer passes are needed and the total accumulated dispersion is much less than in the regenerative configuration. The repetition rate of the output pulses from multipass amplifiers is given by the pump laser ($\sim$10 Hz to 10 kHz). At 1 kHz, 15-fs pulses are obtained with a pulse energy of 1 mJ [4]. A multipass system with sub-30–fs pulse durations which delivers $\sim$1.4 mJ at 5 kHz was recently reported [5].

In regenerative amplifiers, the pump-signal overlap does not change on successive passes through the gain medium. Therefore, this design is more suitable when a high number of passes in the crystal is required. At 5 kHz, 30-fs pulses are obtained in a single-stage regenerative amplifier system showing saturation after about 20 round trips [6]. Furthermore, the highest repetition rates ($>$10 kHz) are only possible with CW pumping. In that case, a Q switch in the amplifier cavity is used to suppress ASE and achieve optimal amplification. The upper limit of the repetition rate is then imposed by the radiative lifetime of the Ti : sapphire ($\sim$3 μs) to $\sim$250 kHz. At this repetition rate, pulse energies of $\sim$3 μJ at a pulse duration of $<$60 fs can be achieved with a commercially available system (RegA 9050, Coherent) based on the setup of [7]. However, the maximum energy storage occurs at a repetition rate of 100 kHz.

It should be noted that a combination of different amplifiers allows peak powers of terawatts [8] with femtosecond pulses at low repetition rates (up to 1 kHz). These multistage systems [9], [22], [23] are capable of producing peak intensities exceeding $\sim 10^{19}$ W/cm^2, i.e., an intensity regime where relativistic effects play a major role in the interaction of light with matter.

The tabletop system presented here can achieve an intensity of more than 5.10^{14} W/cm^2 (f-number 8) at a repetition rate of 100 kHz. It proves to be a perfect tool for investigating above-threshold ionization and high-harmonic generation phenomena [10], [24], [25]. 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.

II. DESCRIPTION OF THE LASER SYSTEM

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

A. Ti : Sapphire Oscillator

A standard Kerr-lens mode-locked oscillator generates the pulses to be amplified. The mean output power is 200 mW at

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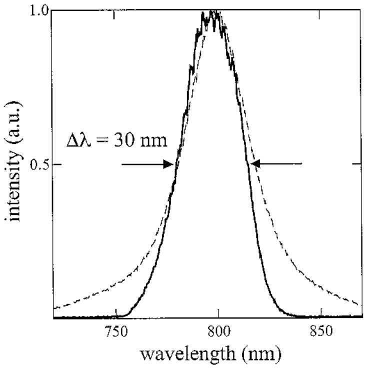

Fig. 1. Power spectra of the oscillator (dashed line) and regenerative amplifier (solid line) outputs.

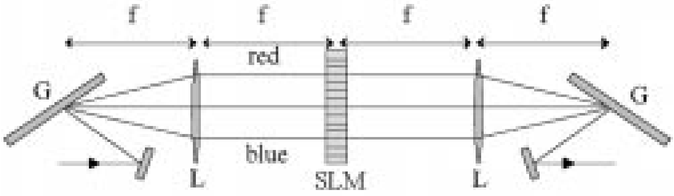

Fig. 2. 4f setup with achromatic spherical lenses (L) and spatial light modulator (SLM) in the Fourier plane. The diffraction gratings (G) are nearly at the Littrow angle.

a repetition rate of 78 MHz. Group velocity dispersion (GVD) control is achieved through a prism pair [11] and three chirped mirrors [12], [26]. This leads to a spectrum of 35 nm (Fig. 1) and a pulse duration of about 20 fs. Directly after the cavity, the direction of the oscillator beam is stabilized with a set of quadrant diodes and piezo-driven mirrors. This is very convenient, since it makes the whole system independent of any adjustment on the oscillator.

B. Phase Modulator in the 4f Setup

While the lion's share of dispersion is compensated after amplification, which will be discussed below, we precompensate the rest with a phase modulator in a 4f setup. It consists of two 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 (Fig. 2) [13], [27]. The modulator is controlled via a GPIB interface and programmed by an evolutionary algorithm with a scheme similar to that used in [14]. This is illustrated in Section III. The angle of incidence onto the first grating is as close as possible to the Littrow angle. The overall transmission of the system is 50%. Spherical lenses are used instead of cylindrical ones since the not-yet-amplified pulses cannot damage the liquid crystal. Nevertheless, we use a shutter to prevent accidental strong focusing of continuous-wave radiation on the SLM when the oscillator is not mode locked.

C. Regenerative Amplifier

After passing through the 4f setup, a proper choice of focusing mirrors matches the input beam to the mode of the amplifier cavity. The oscillator pulses are not stretched and seed a commercial regenerative amplifier (RegA 9050, Coherent—see 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 our experiments. 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. 1).

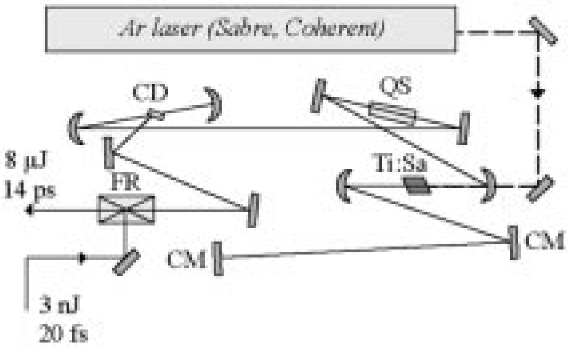

Fig. 3. Scheme of the regenerative amplifier. Ti : Sa—Ti : sapphire crystal. CM—TOD chirped mirrors. CD—cavity dumper. QS—Q switch. FR—Faraday isolator.

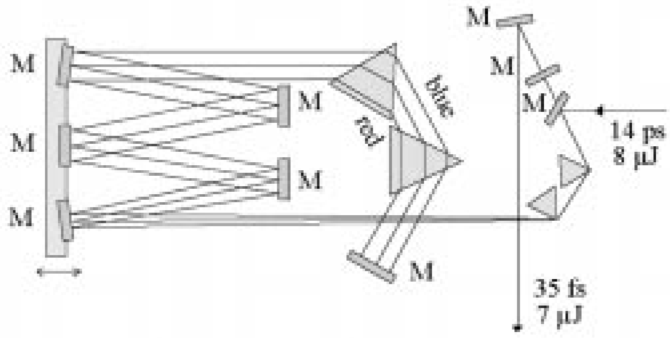

Fig. 4. Prism compressor of Proctor—Wise type. Prism material—S LAL 59 (OHARA). M—broadband dielectric mirrors, three of them mounted on a common translation stage.

D. 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 [15]. This reduces the length by a factor of $\sim$4 in relation to a standard Fork compressor [11] with the same type of glass. The choice of the special glass (S LAL 59, OHARA) is discussed in detail in the following section. The prism separation, adjustable with a movable 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

TABLE I
SIGNS OF THE SOD, TOD, AND FOD DISPERSION FOR OPTICAL MATERIAL, A GRATING COMPRESSOR, AND A PRISM COMPRESSOR

	SOD	TOD	FOD
Material	+	+	+/−
Grating compressor	−	+	−
Prism compressor	−	−	−

total transmittance of the compressor is almost 90% with an output energy of 7 μJ.

The prism compressor, the TOD mirrors, and the phase modulation applied to the SLM allow precise dispersion control and generation of pulses with a duration of 35 fs.

III. DISPERSION COMPENSATION

Control of the dispersion in all orders is crucial for the pulse compression in the ultrashort time domain. In the following, first the material dispersion of our laser system is presented; then the design of the compressor and the choice of the prism material are discussed; finally, it is shown how the compensation of large amounts of higher order dispersion is achieved with chirped mirrors and a phase modulator. The dispersion control scheme extends that presented in [16], [28], since it allows, in principle, compensation in all orders.

Many CPA systems include a stretcher stage before amplification. Our laser, on the other hand, 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 (100 kHz) 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 SOD (SOD $= +100\,000$ fs^2) is produced. The positive TOD (TOD $= +76\,000$ fs^3) also affects the temporal pulse shape, while fourth-order dispersion (FOD) is small (FOD $= -28\,000$ 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], [21].

The absence of a dedicated stretcher stage, present in many femtosecond laser chains, is a great advantage with respect to the complexity of the system. However, clever alignment of the grating stretcher and compressor allows compensation of not only second order, but also higher order dispersion [3], since these systems provide the possibility to adjust the separation and the angle of incidence on the gratings [17], [29]. In this sense, using a prism compressor without stretcher reduces the number of parameters to adjust the dispersion. This is regarded as a disadvantage, since new methods of controlling higher order dispersion have to be found.

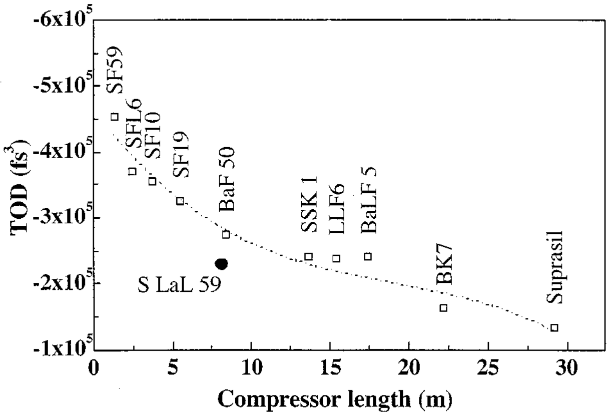

Fig. 5. Calculated TOD and compressor length needed to compensate for the SOD introduced by the amplifier, for different types of glasses.

Despite this and the large dimension required, the choice of a prism compressor can be motivated as follows. First, the efficiency (>80%) is higher than that of the widely used grating compressor (ca. 60%). Second, the TOD of the prism compressor is negative, while in conventional grating compressors it is positive. Table I summarizes the signs of the first orders of dispersion for an optical material, a grating compressor, and a prism compressor [3]: while the grating compressor increases the TOD of the amplifier, the prism compressor balances it. In other words, after compensating for the SOD, the prism compressor minimizes the TOD.

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).

In ultrashort laser physics, the standard material with the lowest dispersion is Suprasil. It would leave a relatively low residual TOD, but would require an inconvenient length of 29 m. On the other hand, highly dispersive glasses such as SF59 shorten the compressor to only 1.3 m, but the residual TOD would require too many reflections on the TOD mirrors in order to be compensated. A good compromise is afforded by using the special glass S LAL 59 (OHARA). The length of

TABLE II
DISPERSION BALANCE IN THE LASER SYSTEM, WITHOUT USING THE SLM: SOD, TOD, AND FOD DISPERSION

Dispersion	SOD (fs^2)	TOD (fs^3)	FOD (fs^4)
RegA / RT	+5 560	+4 240	-1 550
Prism compressor / mm	-12.36	-28.36	-55.23
TOD mirror / reflection	+130	+1 800	+10 000 (?)
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	+1 000 000 (?)
Residual dispersion	≈ 0	≈-3 000	≈+500 000 (?)

the compressor is 8 m (as short as for BaF50) and the residual TOD is $-230\,000$ fs^3 $+$ $76\,000$ fs^3 $=$ $-154\,000$ fs^3 (as low as for LLF6). Since each passage on a TOD mirror introduces approximately +1800 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 (five reflections per round trip, giving 90 reflections) and some additional ones outside the cavity (ten reflections) for fine adjustment. The corresponding total length of the compressor is 9.15 m.

Table II 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 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. Nevertheless, it can be stated that the output pulses are characterized by a compensated SOD, a very low residual TOD, and a high residual FOD.

Fig. 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. It 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 is 3 μm. As already mentioned, the SLM is placed in the Fourier plane of the 4f setup (see Fig. 2), where optimum spatial separation of frequencies occurs. 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/pix. 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 should not exceed π [18]. For a purely quadratic, cubic, or quartic phase distribution, this implies —in our case—a limitation of 5.10^3 fs^2, 5.10^4 fs^3, and 8.10^5 fs^4, respectively, for the maximum SOD, TOD, and FOD applicable. The simultaneous presence of terms of different sign in the phase expansion may eventually lead to even increased acceptable values. Moreover, large phase gradients in the border of the array do not affect the phase modulation, since the actual spectrum is incident only on the central pixels of the SLM mask. For example, applying the Nyquist theorem only to the 64 central pixels, we estimated possible values of 10^4 fs^2, 2.10^5 fs^3, and 8.10^6 fs^4 for the SOD, TOD, and FOD, respectively. 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.

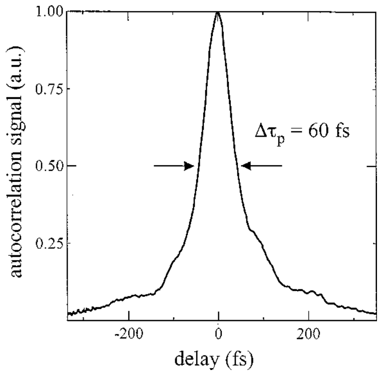

Fig. 6. Noncollinear autocorrelation of the amplified and compressed pulses without SLM in operation. A Gaussian shape is assumed for determination of the pulse duration.

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. Adjustment of the voltage of each pixel for maximum SH represents an optimization problem which is solved with an evolutionary algorithm [4], [14], [18]. Convergence of the procedure [Fig. 7(a)] is rather fast 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

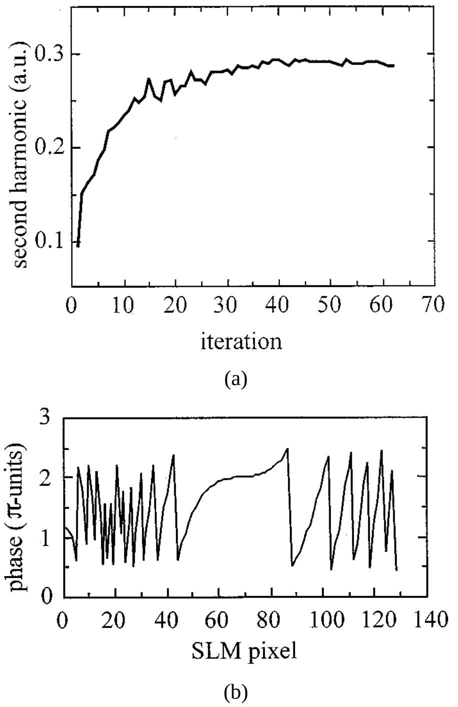

Fig. 7. (a) Convergence of the SH signal while running the evolutionary algorithm. (b) Typical phase distribution applied by the SLM for fine control of the higher order dispersion. The shape clearly indicates the presence of a positive TOD term.

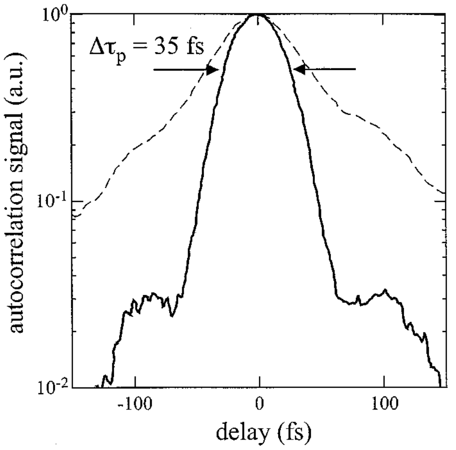

Fig. 8. Noncollinear autocorrelation (semilogarithmic scale) of the amplified and compressed pulses with SLM in operation (solid line). For comparison, the same autocorrelation of Fig. 6 (without SLM) is also shown (dashed line). A Gaussian shape is assumed for determination of the pulse duration.

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—see Fig. 3). The typical phase function retrieved by the algorithm is shown in Fig. 7(b). This distribution compensates for the higher orders and, as expected, is dominated by a positive TOD term.

Fig. 8 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, in principle it is possible to use differential rates as feedback, allowing the evolutionary algorithm to selectively optimize different physical processes as in [19] and [30]. Convergence of the procedure is fast (typically 2–3 min) and, in order to improve the long-term stability of the system, it can be conveniently repeated.

IV. 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 1–10 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 [10], [24], [25], and, in particular, coincidence techniques requiring very low probability of an event per laser shot (e.g., COLTRIMS [20], [31]). With respect to these applications, the great advantage of using the SLM is, as outlined in Section III, the possibility of obtaining the shortest pulses in the interaction region. This allows the study of elementary atomic processes at the highest intensities available at this repetition rate.

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