Generation of 135 fs pulses of variable pulse front tilt by spatially-evolving chirped-pulse amplification at 248 nm

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It has been shown previously that a spatially dependent negative chirp develops, accompanied by a tilted pulse front, when a pulse traverses a single dispersive element. In case of a positively chirped pulse perfect pulse compression can be achieved at a certain plane. In this paper it is demonstrated experimentally that this plane can be imaged, preserving the compressed pulse duration in the plane of the image, and allowing a continuous change of the pulse front tilt through the variation of the magnification. With the insertion of an amplifier just before the imaging element, spatially-evolving chirped-pulse amplification is accomplished. Consequently the amplifier sees a stretched pulse, hence a lowered peak power, while a single lens (or mirror) following the amplifier is enough to create the desired pulse front with the minimum pulse duration at the position of a target. With the use of this technique 248 nm, 135 fs pulses are created at the target plane while the pulse duration in the amplifier is several ps. The spatial evolution of the chirp and of the temporal and spectral properties of the pulse is followed.

1. Introduction

Recently we have shown [1] that a single dispersive element not only tilts the pulse front [2,3] but also introduces a spatially-evolving negative chirp characterized by the temporal dispersion constant ($\mathrm{d}T/\mathrm{d}\lambda$) as

$$\mathrm{d}T/\mathrm{d}\lambda = (\lambda/c)\,(\mathrm{d}\epsilon/\mathrm{d}\lambda)^2\, l\,, \qquad (1)$$

where λ is the wavelength of radiation, c is the speed of light, $\mathrm{d}\epsilon/\mathrm{d}\lambda$ is the angular dispersion of the dispersive element, and l is the pathlength travelled by the pulse following the dispersive element. It was already shown [4] that a similar formula describes the spectral dependence of the delay in conventional compressors consisting of a pair of identical gratings [5] or prisms [4,6], where l means the separation of the dispersive elements. However – as it has been pointed out in ref. [1] – the spatial development of the negative group velocity dispersion (GVD) – described by eq. (1) – is the result of lateral displacement of the tilted pulse fronts of different spectral components due to the dispersion of a single dispersive element. This is shown schematically in fig. 1 (taken from ref. [1]) for a grating and for a positively chirped input pulse. In this case – due to the negative chirp of the grating – pulse compression occurs in a certain plane (denoted as target-plane in fig. 1). If the positive chirp of the incoming pulse is characterized by $\mathrm{d}T/\mathrm{d}\lambda$, the optimum separation of the target plane and the grating (l) corresponding to optimum pulse compression is given by eq. (1).

It is seen from eq. (1) that in order to get constant GVD across the beam l must be the same for different parts of the beam. If the beam is used for travelling-wave excitation (TWE) of targets – as it is proposed for the realization of X-ray lasers [7] – the target to be pumped has to be parallel to the grating.

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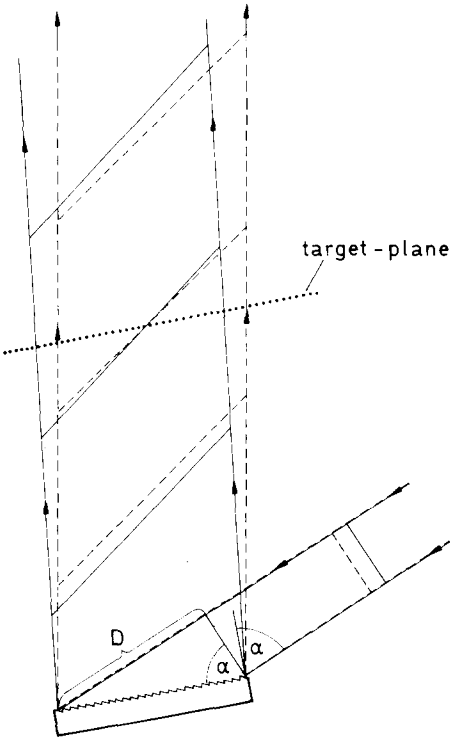

Fig. 1. Schematic of the pulse fronts of the red (dashed line) and the blue component (solid line) of a positively chirped pulse after diffraction on a grating (taken from ref. [1]).

In this case – as also shown in ref. [1] – the maximum pulse front tilt referred to the target-plane is limited to $\gamma < 45°$. However, for travelling-wave excitation of targets having a group velocity index at the wavelength of radiation to be generated $n \geqslant 1$, a pulse front tilt $\gamma \geqslant 45°$ is necessary to get synchronism between the pump beam and the generated radiation. In ref. [1] several alternatives are given how to increase γ to the necessary value. The simplest and most straightforward way is to form a demagnified image of the plane of optimum pulse compression, as shown schematically in fig. 2 (taken from ref. [1]). The positively chirped incoming beam – after it has been diffracted by grating G – is optimally compressed at plane A which is then imaged by an optical image system OS to plane B. Since optical imaging leaves the absolute value of the delay between the two marginal rays unchanged, the increase of the tangent of the pulse front tilt can be calculated from the demagnification M, as

$$\tan\gamma' = M \tan\gamma , \qquad (2)$$

where γ' and γ are the tilt angles of the pulse fronts in the planes B and A respectively.

Assuming a perfect image system in the position of OS – which has to have the same pathlength between any pair of object and image points for any rays and any spectral components – the same compressed pulse duration is seen by plane B as by plane A, while the pulse duration in between these two planes (seen also by OS) is longer. (For further details see ref. [1]).

When following the spatial evolution of the chirp and the pulse duration in the experimental arrangement of fig. 2, one sees that the originally positively chirped pulse – after it is optimally compressed in plane A – becomes negatively chirped and the pulse duration increases until OS up to a value that is roughly the original pulse duration multiplied by the ratio of the distance between A and OS and l. Then the chirp and the pulse duration decrease until both reach their minimum values in the image plane B.

This spatial evolution of the chirp and the pulse duration makes it possible to insert an amplifier-system between plane A and OS, which will then see long pulse duration and therefore moderate intensities. Moreover, a single lens following the amplifier can generate the ultimate shortest pulse duration at the target plane.

In order to minimize the intensity-related problems in short pulse amplifiers, a chirped-pulse amplification scheme has been developed [8], where the pulse duration of the pulse to be amplified is artificially lengthened and shortened in a pulse stretcher and compressor, positioned before and after the amplifier respectively. This technique is successfully applied for Nd:glass and for alexandrite amplifiers. The drawback of this elegant method is that separate systems are used as pulse stretcher and compressor, each consisting of (a fiber or) a pair of gratings, making the whole system complex and limiting the efficiency of coupling the power from the last amplifier to the target. Since the different spectral components are spatially overlapping in the amplifier and are stretched in time, their different (saturation-induced) amplification may cause a narrowed spectrum depending on saturation of the amplifier and thus incomplete compression of the pulse.

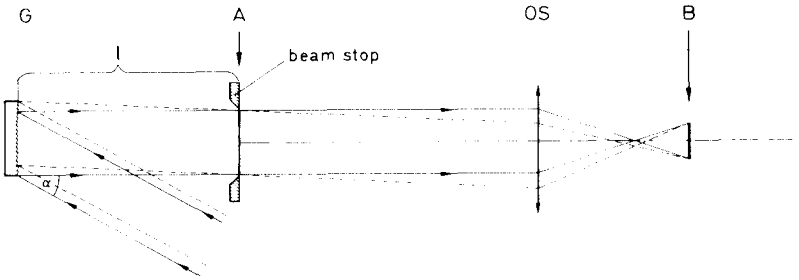

Fig. 2. Schematic arrangement to change the angle of pulse front tilt by optical imaging (taken from ref. [1]).

The above problems are especially important for short pulse KrF amplifiers, due to the much shorter bandwidth-limited pulse width (<100 fs) [9,10], and due to the enhanced nonlinearities at that short wavelength (248 nm).

On the other hand in case of gas amplifiers nonlinearities must be considered mainly at the output windows, and the threshold intensity where nonlinear processes become dominant (several GW/cm^2), is close to the intensity which belongs to optimum (saturated) amplification of subpicosecond pulses. This is due to the much lower saturation energy density compared to that of solid state lasers. It means that in case of gas amplifiers the pulse duration of the pulse to be amplified need not be stretched by as high a factor as in solid state amplifiers ($\sim 10^3$), instead a factor of ~ 10 seems satisfactory.

Short pulse KrF amplification experiments have been carried out in many laboratories [9–14]. In spite of the fact that chirped-pulse amplification has already been suggested also for excimers [15], amplification of only unchirped seed pulses is realized experimentally up to now. Possibly due to the above mentioned nonlinear constraints on intensity, in ref. [13] not the shortest possible pulses were addressed. Only amplification of pulses of several ps duration is presented. Even in those approaches, where the seed pulse duration is close to the KrF bandwidth-limit [9-12,14], during amplification a broadening to several hundred fs occurs due to GVD and self-phase-modulations (SPM). It was found [9,10] that a transform-limited pulse duration can only be achieved through pulse compression following amplification [16]. However, in this case severe losses are introduced in the final beam, using conventional pulse compressors, as in refs. [7,8]. It gets even worse when TWE of targets is needed, necessitating the use of even more complicated optical arrangements [17]. It seems that the combination of the optical scheme in fig. 2 with optical amplifiers can solve the above mentioned problems. With the use of this spatially-evolving chirped-pulse amplification technique the minimum compressed pulse duration with any pulse front tilt could be created at the target plane, using only a single focussing element following the amplifier. This has a great importance in large scale experiments.

In this paper some aspects and a small scale experimental study of the spatially-evolving chirped-pulse amplification technique are presented.

2. Experimental

The above considerations were checked in three experiments. In these experiments a KrF laser system (built at LLG), an improved version of that described in ref. [10] delivering ~ 10 mJ, ~ 500 fs chirped pulses at 248 nm with a repetition rate up to 20 Hz [18] was used. The spectral measurements were performed by a home-made spectrograph with a diode array attached having a resolution of ~ 0.2 Å. For pulsewidth measurements a multiple shot autocorrelator based on two-photon ionization of NO was used (for details see ref. [16]).

In the first two experiments we used the scheme displayed in fig. 2, applying a prism or a grating as a dispersive element in the position of G.

In the first experiment output pulses of the femtosecond KrF laser system were sent through a 45°

prism made of Suprasil. The duration of the tilted pulse fronts was measured by an autocorrelator which was moved along the beam emerging from the prism, until minimum pulse duration was measured (as in ref. [1]).

Directly after the prism the pulse duration was ≈500 fs which decreased to a minimum of 120 fs at a distance of $l=215$ cm measured from the prism (this corresponds to plane A in fig. 2). At this plane we placed a circular aperture into the beam, and a 1:1 image of this plane was made by a fused silica lens of 2 m focal length. When the autocorrelator was put in the image plane (which corresponds to plane B in fig. 2) the pulse duration obtained there was again 120 fs.

In the second setup the output pulse of the KrF laser was compressed by the use of a 3600 line/mm grating. Comparing its temporal dispersion constant with that of the prism used in the previous experiment, the plane of optimum compression is 4 cm away from the grating, obtained from eq. (1). For technical reasons we did not measure the pulse duration there. We imaged that plane applying a ~4 times magnification, with the use of a cylindrical mirror of $R\approx 600$ mm. When cylindrical imaging is performed in the plane of the dispersion of a dispersive element, the angle of the pulse front tilt can be varied by different settings of the magnification according to eq. (2) while leaving the perpendicular dimension of the beam unchanged. This provides the possibility to set independently this size of the beam by the use of an additional lens or mirror to the desired value in the target plane.

In this experiment the object and image distances were 38 cm and 140 cm respectively. In the image plane the measured pulse duration was 120 fs as in the earlier cases while at the position of the cylindrical mirror longer than 1 ps pulse duration was measured.

In the third experiment the feasibility of the spatially-evolving chirped-pulse amplification was studied by inserting an amplifier between the two planes of optimum compression (between plane A and plane B in fig. 2). The experimental arrangement used for this purpose is shown in fig. 3. In this arrangement the dispersive element – denoted by G in fig. 2 – is integrated into the KrF short pulse system. The UV part of the system (described in detail in ref. [10]) is modified as shown in fig. 3. The 2 μJ seed pulse of ~500 fs duration is first amplified in the KrF gain module up to 500 μJ. After the beam has passed through a 1:1 telescope with a vacuum spatial filter it falls onto a 3600 line/mm grating. The angle of incidence is adjusted so that the diffracted first order beam is perpendicular to the grating. This is necessary to ensure that the plane of perfect compression is perpendicular to the direction of propagation (see ref. [1]). Assuming the same chirp as before in the first two experiments (which we consider as an inherent property of the UV pulses generated by our dye laser system) optimum compression occurs 4 cm behind the grating. In this position we placed a ~1 mm diameter circular aperture (denoted as object-plane in fig. 3). The beam passing through this aperture is sent again in the KrF amplifier tube for the second pass. Due to the dispersion of the grating, the different spectral components travel along different paths in the amplifier. All spectral components reached saturation. A fused silica lens of 2 m focal length, positioned behind the amplifier, imaged the object plane with a magnification of 2.5 to an image plane. The pulse duration measured just after the $f=2$ m lens is 8 ps as shown in fig. 4a. This long duration, seen also by the amplifier, is the result of the pulse-stretching effect of the grating behind the plane of optimum compression (see also fig. 2). However, when increasing the distance between the lens and the autocorrelator, a decreasing pulse duration is seen, until it reaches its minimum value some ~7 m far from the lens, at the position of the image plane. The autocorrelation trace recorded in the image plane is displayed in fig. 4b, showing a 135 fs minimum pulse duration.

There is a very important observation in association with this pulse duration. Inspection of the pulse spectrum just after the first amplification (fig. 5a) reveals that the corresponding transform-limited duration to the 1.95 Å broad spectrum is 330 fs. This means that in the plane of the aperture the pulse width cannot be shorter than 330 fs. The fact that after imaging this plane through a saturated and inhomogeneously broadened amplifier yields a much shorter, 135 fs pulse length is explained as follows. The chirp is introduced by the dye laser system in the form of the appearance of far-reaching low-intensity spectral wings that are hardly seen on the

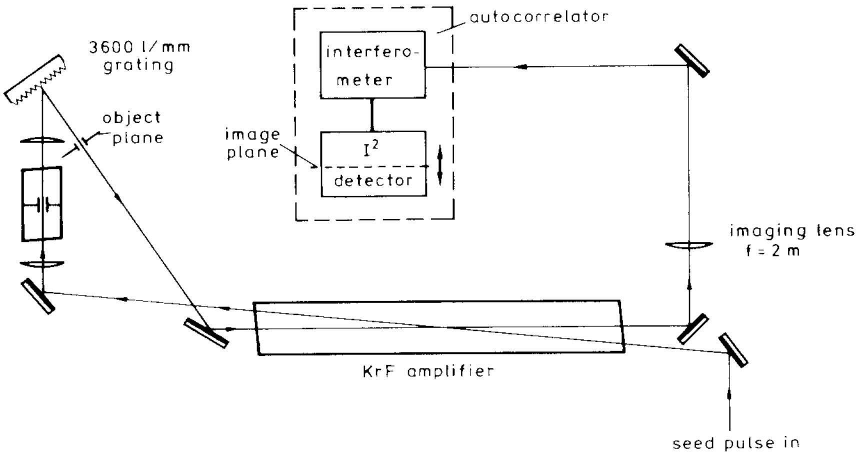

Fig. 3. Experimental setup to demonstrate the spatially-evolving chirped-pulse amplification.

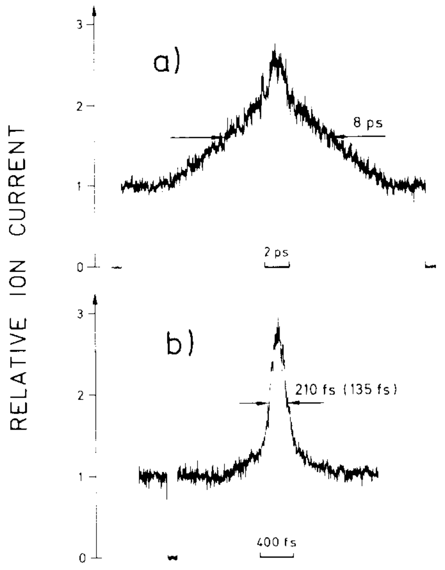

Fig. 4. Autocorrelation traces recorded (a) just behind the $f=2$ mm lens, and (b) in the image plane (see fig. 3).

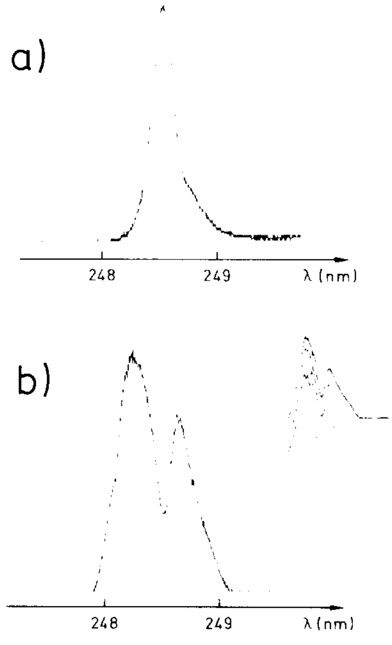

Fig. 5. Pulse spectra after (a) the first and (b) the second amplification in KrF (see fig. 3). The inset shows records of the spectra as a sharp edge was moved across the beam just behind the amplifier.

spectrum of the seed pulse [9,10]. Even after the first non-saturated amplification in KrF there is only a little sign of the enhancement of the wings. However, these spectral components are present and are dispersed by the grating regardless of their relative amplitude. When this beam is sent through a saturated amplifier with inhomogeneous broadening, the intensity of the wings is raised drastically (fig. 5b). If the chirp is linear across the entire bandwidth, a compressed pulse duration of 110 fs, corresponding to the transform limit of the ~5.9 Å bandwidth, is expected in the image plane. The measured pulse length of 135 fs in fig. 4b is in good agreement with the expectations. So the final short pulse duration is a result of the saturated amplification via enhancement of the spectral wings of the linearly chirped input pulse. One important feature of the described arrangement is that the pulse duration is considerably stretched at the amplifier (including the windows) and the focusing element – where nonlinear constraints on intensity are very important – while minimum pulse duration is obtained at a desired plane (as seen comparing figs. 4a and 4b).

Another interesting feature of this scheme is the spatial separation of the different spectral components in the amplifier. That was experimentally checked by viewing the output spectrum while a sharp edge was moved across the beam just before or just after the amplifier. The influence of this partial beam-blocking on the spectrum is displayed in the inset of fig. 5b. Since the spatially separated spectral components are amplified separately, this arrangement acts as an inhomogeneously broadened amplifier even with homogeneously broadened active medium. This makes it possible to prevent spectral hole burning even in homogeneously broadened amplifying media. Therefore saturated amplification can result in a broad spectrum necessary to obtain short pulses.

The change of the tilt angle of the pulse front in the target plane through different choice of the magnification of the image system was checked by putting a streak camera (Hadland Imacon 500) in the position of the target plane whose slit was set to be parallel with the plane of fig. 3. With this measurement different arrival times of different parts of the beam could be visualized. Within the accuracy of this measurement, agreement is found between the measured and the expected values of the pulse front tilt for different magnifications.

Since in our experiments the ideal image system at the position of OS was substituted by a single lens or a mirror, slight curvature of the pulse front in the image plane is expected. Work is in progress to measure this curvature and to determine the tilt angle of the pulse front with improved accuracy.

Results concerning this development will be presented in a forthcoming paper [19].

3. Conclusion

We have studied the spatial evolution of the chirp and the pulse duration of an originally positively chirped pulse when it is passing through a dispersive element and a subsequent image system.

It is found that – due to the spatially dependent negative GVD of the dispersive element – the pulse duration first decreases until it reaches its minimum value at the plane of optimum compression. Then it starts to increase again, but the sign of the chirp becomes opposite. When an image system creates the image of the plane of optimum compression at the target plane, the pulse duration increases up to this image system and then decreases again until it reaches its minimum value in the plane of the target.

This spatial evolution of the pulse duration makes it possible to simulate the conventional chirped-pulse amplification technique in a much simpler way, only by inserting an amplifier into the beam where the pulse duration is stretched. In this way the amplifier and the target can be separated only by a lens or a mirror without the need of separate pulse stretchers and compressors.

Since in the target plane the pulse front is tilted, and its tilt angle can continuously be changed through the change of the magnification of the image system, this arrangement is ideally suited for TWE of targets.

Another advantage of this technique beyond its simplicity and good efficiency is that the different spectral components can be amplified independently, therefore the final spectrum can be controlled even for homogeneously broadened amplifiers independently of the level of saturation.

For the above reasons this technique can find many applications in the field of target experiments, performed with fs pulses.

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