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Spatio-temporal analysis of the distorted chirped pulse amplification laser beam in focus

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A spatio-temporal study in focal point of the distorted laser beam after propagation through an optical chirp pulse amplification (CPA) system was developed. This study is based on numerical simulation using the ray-tracing model from Rayica module of MATHEMATICA and it relates the spatial and temporal behavior of the distorted beam in focal region in case of user-induced misalignments in grating stretcher-compressor system. Consequently, the misalignments influence the focal structure of the electromagnetic distribution of the CPA laser beam. The results are relevant for different applications which use CPA systems with needs of high quality laser beam profile in focus.

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1. Introduction

Chirped Pulse Amplification (CPA) method has been demonstrated in the last decades as an important tool for generating ultra-fast and ultra-intense laser pulses. Today, CPA technique is incorporated in most of the ultra-short laser systems and it makes possible to be implemented in a wide range of applications in science (atomic and condensed-matter studies, plasma, nuclear and high-energy physics, general relativity and cosmology, astrophysics, femtochemistry, nonlinear optics, studies of ultrafast phenomena by the pump-probe method and time-resolved spectroscopy, two- and three-photon microscopy, high-order harmonic emission, zettawatts generation), technology (control of elements for microelectronics, precision machining, terahertz imaging systems, isotope separation.) and medicine (optical coherent tomography, precision surgery, fabrication of micro-stents in cardiology) [1-10].

While CPA method provides ultra-intense laser pulses, the complementary studies are oriented in the direction of “spatio-temporal distortions” which belong to ultrafast optics because the stretching, amplification and recompression of ultra-short pulses all involve the introduction and removal of massive spatio-temporal aberrations [11].

One of the most common spatio-temporal distortions introduced by CPA technique is the spatial chirp which is a geometrical property introduced by dispersive elements with angular dispersion such prisms and gratings. It remains even after the second prism or grating while the angular dispersion is usually zero. To remove the spatial chirp, another inverted pair of prisms or gratings is needed according to the alignment limitations. Beside spatial chirp, angular dispersion produces also the tilt of the pulse front which is a particular kind of spatio-temporal distortion usually considered equivalent phenomena with the angular dispersion process itself [12].

It is generally desired that the output CPA pulses to be free of spatio-temporal distortions but due to the common improper alignments in the CPA system and to the broadband features, the ultra-short pulses are often affected by such distortions causing a wide range of problems such intensity reducing and temporal resolution alteration [13].

In this paper, we developed a numerical study regarding the spatial distortions effect of the laser beam wavefront in focal region after the propagation through the optical CPA system described in [14]. The intensity patterns at the output of CPA were generated using MATHEMATICA software according to the optical path from the CPA laser system.

The study was made for several distinct incident angle values on the diffraction grating, monitoring the effect of the spatial chirp and the pulse front tilt, on the focal intensity profile after the CPA optical system, analyzing both spatial and temporal aspects. The results are relevant for future experiments using our CPA optical chain.

2. Optical stretcher-compressor system

Our CPA laser system used in this study was built to work together with a commercial femtosecond laser system (Clark MXR-2101) also based on the CPA method, having the central wavelength of 775 nm, pulses duration of 230 femtoseconds, about 8 nm spectral bandwidth FWHM, running at 2 kHz with 0.7 mJ/pulse. One of the most important experimental applications of this external CPA chain was multiple pulses generation when the system architecture was modified in order to produce two collinear pulses with complementary spectral components [15].

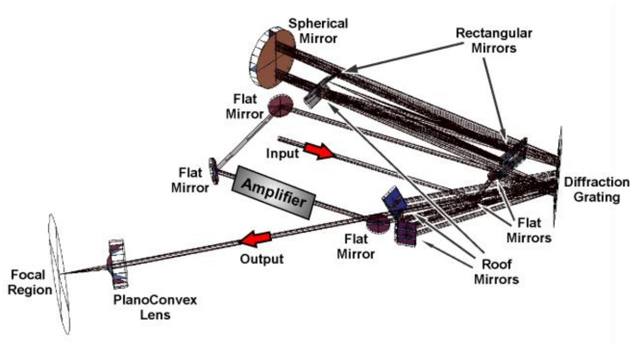

Fig. 1. Rayica ray-tracing of the stretcher-compressor system having only one diffraction grating with incident angle of 23º, after [14].

Before the construction, the stretcher-amplifier-compressor system was first designed using ray-tracing model from Rayica module of Mathematica which uses a numerical ray-tracing model to extract the wavelength-dependent phase for each ray.

As it can be seen in Fig. 1, both the stretcher and the compressor use the same diffraction grating. The fixed top roof mirror from the stretcher ensures the double passing of the optical system. Both roof mirrors from the compressor compensate for the optical path differences introduced by the stretcher. The stretcher and the compressor use the same incident angle on the diffraction grating.

Initially the optical CPA system was projected to present no spatial distortions of the Gaussian beam using the same incident angle of 23º both in optical stretcher and compressor. The focusing system is composed of a plano-convex lens which is positioned on the output of the CPA system having the focal distance of 100 mm. The focal intensity patterns at the output of CPA were generated using the same package Rayica from MATHEMATICA software in accordance to the optical path from the CPA laser system.

3. Results and discussions

According to our optical stretcher-compressor laser system described before, we analyze the laser beam intensity distribution in focus after the CPA chain by varying the diffraction grating incidence angle in the range of 15-31º with 4º step taking into account the spatial distortions introduced by the CPA method itself (e.g. spatial chirp, pulse front tilt).

We collected the information related to the optical path and the profile intensity of the CPA focused beam after the propagation through the optical stretcher and compressor using the same numerical ray-tracing model Rayica, package of Mathematica.

According to the main principle of the CPA method, the spatial chirp is introduced during the stretching process by the delay between the bluer part of the spectrum and the redder one while travelling through the stretcher. In this way, different optical paths are introduced at different wavelengths in the lasing range, producing the group velocity dispersion. It is well known that the stretching efficiency depends on the spectral width of the input beam, grating incident angle, grating parametrical properties, optical system dimensions and the number of the passes through the stretcher.

In this paper, first we analyzed the laser pulse wavefront after the optical stretcher and compressor (Fig. 2(a),(b)) according to the incident angle variation and we generated for each case the laser beam intensity distribution. Fig. 2(a) shows the angularly dispersed pulse with pulse front tilt in presence of spatial chirp. The pulse front tilt results in the output beam due to the group-velocity dispersion which drives the redder side of the beam to emerge earlier than the bluer side.

Fig. 2(b) illustrates the beam intensity profile after the compressor which has the role to compensate the optical distortions introduced by the stretcher. This shows the importance of establishing the optimum value of the grating incident angle with minimum spatial distortions in our CPA laser system.

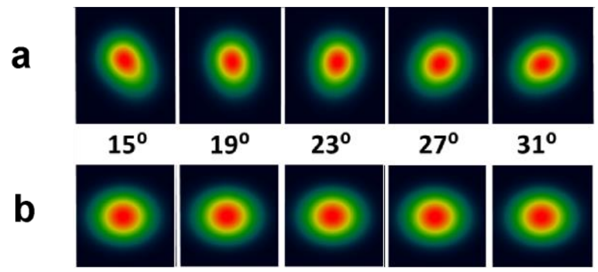

Fig. 2. (a) The Gaussian beam intensity profile for different grating incident angles illustrating the angularly dispersed pulse with pulse-front tilt after the stretcher. (b) After the compressor the angular dispersion is compensated.

It can be observed that the angular dispersion explained by pulse front tilt is compensated after the beam propagation through the compressor having similar aspects and dimensions on both axis while spatial deformations are still present due to the uncompensated spatial aberrations in the CPA chain. These spatial distortions can be easily compensated using modern methods which involve opto-electronic elements such as spatial light modulators being controlled by iterative Fourier Transform algorithms [16, 17].

Taking into consideration these uncompensated aberrations after the CPA chain together with the effect introduced by the grating incidence angle variation, we analyze the effect of the spatial distortions on the CPA beam intensity distribution in the focus.

In our case, the spectral modulation produced by the stretching process is not completely compensated by the compressor and it results in a difference between the blue part and the red part of the pulse of 0.038 units in focus point (Fig. 3(a)), explained in terms of central frequency

(ω_L). This measurement was made for the ideal case with incidence angle of 23^0, related to the end position of each ray (x/λ).

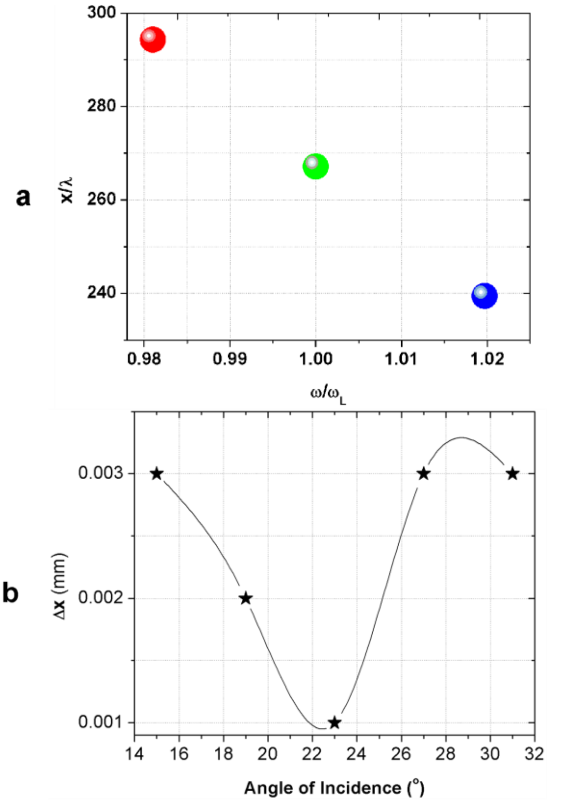

Fig. 3. (a) The spatial chirp after the CPA chain in focus for the ideal case with incidence angle of 23º. (b) The differences between the optical paths of the rays in focal point in case of incidence angle variation in the range of 15-31º with 4º step.

By varying the incidence angle in the range of 15-31º with 4º step, we evaluated the differences between the optical paths length of the spectral components (Δx), after the CPA chain, in focal region. The evolution of Δx is presented in Fig. 3(b).The incidence angle variation has a significant influence on the length of the optical paths of the rays, showing the importance of the alignment accuracy in the optical CPA systems. The minimum value of the optical length is equal to 0.001 mm, obtained for the ideal case with incidence angle of 23º and it increases up to 0.003 mm while the angle of incidence is varied symmetrically around the ideal case.

The variation of the incidence angle also influences the size of the focal spot of the laser beam after the CPA chain. In Fig. 4(a) we represented the focal spot of the laser beam after the CPA system in presence of incidence angle variation in the same range previously mentioned. As it can be seen, the focal intensity distribution gains a non-uniform shape explained by assuming that our optical system was not precisely aligned having left spatial distortions different from zero.

The evolution of the laser beam spot size in focus is illustrated in Fig. 4(b). The shortest focal intensity distribution radius was obtained at incident angle of 23º and it measures 8 µm, in accordance with the laser beam spot equation: $w = M^2 \lambda f/\pi w_1$, where λ is the laser wavelength, f is the focal distance of the lens and w_1 the radius of the beam spot before the lens (in our case w_1=3 mm). Since the initial beam we used in the numerical simulation is perfect, it doesn't present any deviation from the fundamental TEM00 mode structure and the beam quality factor (M^2) is equal to 1.

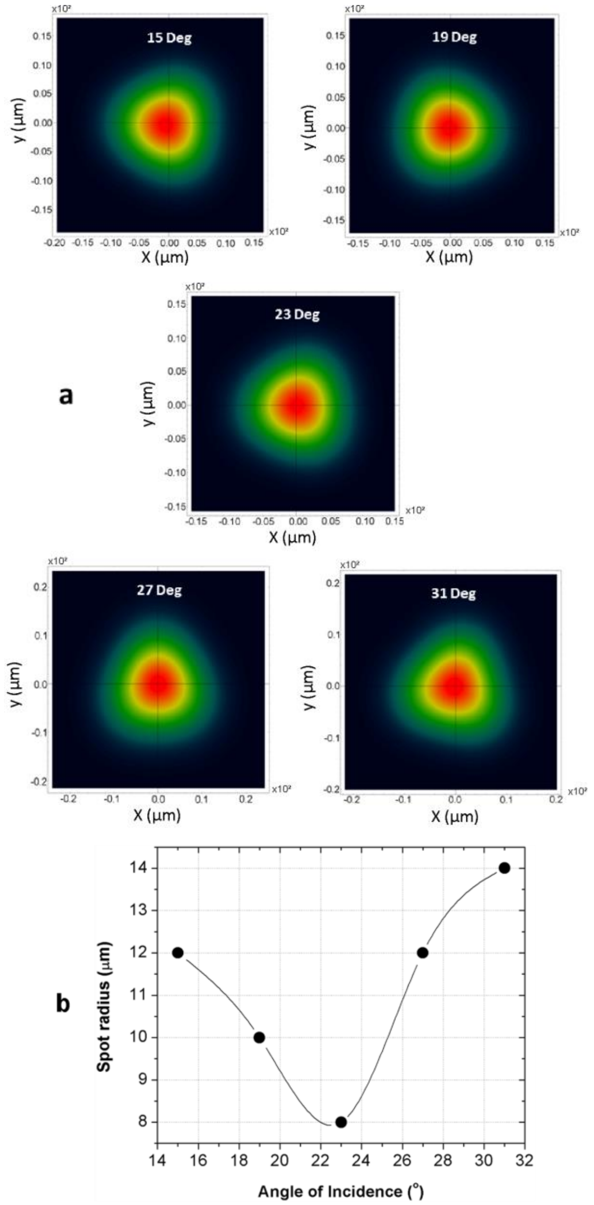

Fig. 4 (a). Beam spot size at focus after the CPA chain. Fig. 4(b) shows how the slightly misalign in the stretcher-compressor system by varying the incident angle on the diffraction grating in the range of 15-31º with 4º step influences the spectrum size in the focus.

The effect of the spatial distortions on the pulse duration after the CPA chain was also investigated. To evaluate the temporal aspect of the beam after propagation through the optical CPA system, the numerical results obtained after the ray-tracing are Fourier analyzed in Mathematica in order to produce the temporal intensity profile of the pulse. For this, we used 2^{13} sample points with a 4 fs temporal resolution.

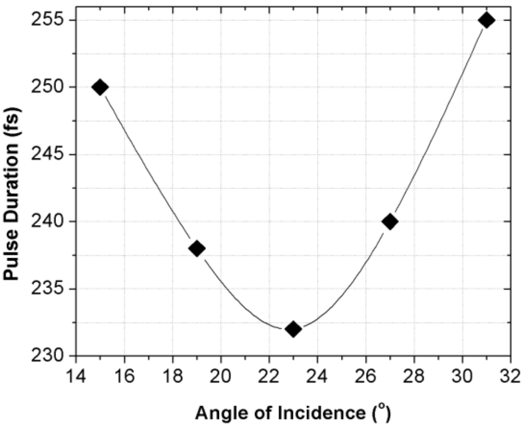

Fig. 5. Pulse duration in focal point after the CPA chain in case of incidence angle variation in the range of 15-31º with 4º step.

In Fig. 5, it can be observed that the pulse duration is consistently sensitive to the incidence angle variation; hence the alignment of the CPA grating can be done more precisely by measuring the spatial distortions in terms of spatial chirp and pulse front tilt, than by monitoring the pulse duration. In these circumstances, we obtained for each 4º grating deviation around the ideal value of 23º, a systematically increase of the pulse duration. Note that the pulse duration plays an important role on CPA spatial distortions investigation, being extremely sensitive on user-induced or spontaneously misalignments in the optical stretcher-compressor system.

4. Conclusions and perspectives

We investigated the spatio-temporal behavior of the CPA laser beam in focal region in the presence of user-induced misalignment in grating stretcher-compressor. For this, we considered the numerically modeled optical system in Rayica varying the value of the angle of incidence on the diffraction grating in the range of 15-31º with 4º step which employs a different geometry on the CPA system for each case and we analyzed the optical aberrations generated by the spatial distortions such as angular dispersion and spatial chirp.

The final results demonstrate that uncompensated spatial chirp after the CPA chain in presence of user-induced misalignments results in a high order spectral modulation which not only lengthens the pulse duration but also alters the shape of the focal intensity distribution. The dimension of the beam spot diameter presents an increase during the variation of the grating incident angle around the ideal value of 23º. In this way, it was shown the importance of establishing the optimum value of the grating incident angle with minimum spatial distortions in a CPA laser system.

This effect can be used for the stretcher-compressor alignment and characterization in experiments to fine tune the positive and negative chirp of the CPA system and to control the spatial distortions in order to improve the quality of the focused CPA beam profile for ultra-fast micro-processing experiments.

Acknowledgments

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