A numerical method is presented to study the laser beam distortions and their influence on the interference patterning after propagation through an optical chirp pulse amplification (CPA) system. This study is based on numerical simulation using the ray-tracing model from Optica module of MATHEMATICA and it relates the behavior of the distorted beam in terms of spatial distortions in case of user-induced misalignments in single-grating stretcher-compressor system. It was shown that this effect can be used both to control the femtosecond laser interference pattern design and to improve the quality of the CPA beam profile for ultra-fast micro and nano-patterning experiments using multiple CPA laser beams.

Key words: Chirped Pulse Amplification, spatio-temporal distortions, lithographical laser processing, multiple beam interferometry.

1. INTRODUCTION

Laser interference lithography is a flexible and potentially method to produce periodic structures using multiple interfering highly-coherent light beams. In last decades, the interference of laser was used to create periodic structures such as distributed feedback laser, field emission displays, liquid crystal displays, optical gratings, fiber gratings, directed nano-photonics, large area membrane reflectors and anti-reflectors [1–3]. Thus, the lithographical laser processing became a very important topic of interest offering the possibility to achieve micro and nano-structures, fast generated with a high processing control. Lately, ultra-fast lithography method using an interfering femtosecond laser had been implemented progressively as a complex direct processing technique for 1D, 2D and 3D nano-sized and periodic structures generation [4–7]. It was shown that a design interference pattern can be generated by controlling the number of beams [8], phase shift and variation of amplitude between the interfering laser beams [9].
The femtosecond laser systems are usually based on CPA method \cite{10}, in order to generate ultra-short (few-cycle) intense laser pulses \cite{11} with various applications such as free-electron laser experiments \cite{12}, femtosecond synchronization systems \cite{13}, nuclear photonics \cite{14}, the formation of self-guided beam, without Kerr self-focusing \cite{15}, micro and nano-structuring \cite{16} which needs a high quality laser beam profile \cite{17} and simultaneous processing. For this, the CPA method often implements adaptive optics employing diffractive optical elements \cite{18–20} or holographic masks \cite{21}. In this paper we investigate the interference pattern of two and three countering CPA beams respectively by simulation, in the presence of user-induced misalignments. Our optical system was designed with Optica software, a ray-tracing package of MATHEMATICA, following \cite{22}. This optical system was designed to work with a single diffraction grating for both optical stretcher and compressor \cite{23}. This aspect increases the difficulty of the alignment generated by the incidence angle on the diffraction grating. Considering these, we made a study for several distinct incident angle values on the diffraction grating in the CPA optical system, monitoring the effect of the user-induced misalignments on the interference pattern. The interference figure at the output of CPA chain were generated using MATHEMATICA software taking into account the optical path from the CPA laser system. The results are relevant for future interference processing experiments using CPA optical systems.

2. INTERFERENCE PATTERNING USING MULTIPLE CPA LASER BEAMS

The CPA system contains an optical stretcher, an amplifier and a compressor designed to work with a laser system with 200 femtosecond pulses based on the CPA principle, that was used for example in \cite{24–25}. Previous works relate spatio-temporal distortions analysis after propagation through the designed optical CPA system, in case of user-induced misalignments \cite{26–27}. It was shown that uncompensated spatial chirp after the CPA chain results in a high order spectral modulation which not only lengthens the pulse duration but also modifies the laser beam profile. Also, related to the interference pattern distribution, other work was reported in \cite{28}, where a complementary study of electromagnetic field distribution in the focal region using the coherent combination of two laser beams had been performed.

According to these previous studies, in this paper we investigate the interference pattern evolution after the CPA optical system in case of user-induced misalignments using two and three laser beams respectively. The sketch of the CPA optical system together with the adjacent interferometer module are shown in figure 1. As it can be seen both the stretcher and the compressor use the same diffraction grating. The double passing through the optical system is ensured by the
fixed top roof mirror from the stretcher. The optical path differences introduced by the stretcher are compensated by the two roof mirrors from the compressor. The optical stretcher and the compressor use the same incident angle on the diffraction grating. After the CPA chain, the output beam is guided through the interferometer setup, illustrated on the inset picture. The countering beams are generated by the two beam splitters included in the interferometer scheme, with an angle of 41 degree between the beams axes and normal direction which coincides with the third countering CPA beam. The simulated interference patterns are obtained using a numerical ray-tracing model and it is investigated for each case of user-induced misalignments in the CPA chain, taking into account the uncompensated spatio-temporal distortions after the compressor.

Fig. 1 – Optical ray-tracing of the CPA interferometric laser system.

3. NUMERICAL SIMULATIONS AND RESULT DISCUSSION

Initially, the optical CPA system was projected to present no spatial distortions (i.e. pulse front tilt or angular dispersion) using the same incident angle of 23° both in optical stretcher and compressor. This was assessed as the optimum value of the incident angle on the single diffraction grating according to the multiple distortions studies elaborated for our CPA laser system. By using a single diffraction grating for stretcher and compressor the compensation of the distortions introduced by the optical stretcher was simplified. For this, it was considered the previous studies which demonstrated that the pulse front tilt was completely compensated after the compressor in same user-induced misalignment conditions while the angular dispersion presents a negligible rate variation (~0.004 rad/nm) [26] during the grating incident angle variation in range of 15–31° with 4° step.

In this work, first we analyzed the structures generated by two interfering CPA beams. In our simulation, the user-induced misalignments consist of variation of the incident angle on the diffraction grating around the ideal value of 23° in
range of 22.9–23.1° with 0.05° step in the CPA system. For each case, we obtained different interference patterns, following the ray-tracing numerical model, taking into account the rays path and the normal incidence of the laser beam. The position of the central wavelength of the CPA beam on each optical component varies for each value of the grating incident angle. The interference pattern variation as a function of incident angle on the diffraction grating, in case of two CPA beams, is illustrated in figure 2. It is shown how the slightly misalign in the stretcher-compressor system by varying the incident angle on the diffraction grating in the range of 22.9–23.1° with 0.05° step influences the fringes periodicity, in case of two laser beams interference. A periodically increase of the interfringe was observed, in range of 141–242 μm, during the user-induced misalignments as shown in Figure 2.

This aspect can be explained both in terms of the interfering beams phase shift introduced by the user-induced misalignments and also from the uncompensated spatial distortions from the CPA chain which are still present after the compressor and they lead to a spatial deformation of the laser beam profile. The second mentioned approach was investigated before for grating incident angle variation in range of 15–31° with 4° step and it had been shown that during the user-induced misalignments the CPA beam intensity profile has similar aspects and

Fig. 2 – Comparison of the two beams interference patterns in case of the variation of the incident angle on the diffraction grating in the range of 22.9–23.1° with 0.05° step and calculated values of fringes periodicity in the presence of user-induced misalignments.
dimensions on both planes while spatial deformations are still present due to the uncompensated spatial distortions in the CPA system. The beam phase shift is calculated from the ray-tracing model of the laser system at the output of the compressor for each case of user-induced misalignments in the CPA chain.

The effect of these two approaches on the laser beams interference can also be observed in case of three overlapping beams, when uniform interference patterns in lattice are formed, as shown in Figure 3. This set of five pictures presents the evolution of interference pattern in terms of shapes rotational angle ($\alpha$) and shapes spacing ($d$) in presence of grating incident angle variation in the same range, previously mentioned. The lowest incident angle value (22.9°) induces very elongated ellipsoid shapes with a spacing of about 141 µm with the corresponding shapes rotational angle of 88.5° and phase shift of $(5/7)\pi$. In the case of $(6/7)\pi$ phase shift corresponding to 23.1° incident angle, the $\alpha$ parameter encounters a decreasing of about 30° and the shapes spacing is significantly expanded to 242 µm.

![3D Interference Plot](image)

**Fig. 3** – Three beams interference pattern for regular structures formed by asymmetric interference in presence of grating incident angle variation.

It is interesting that the shapes size obtained for each case uniformly increases, generating in this way a uniform lattice, with a well-defined shape spacing. In the
case of 23.05° grating incident angle the shape of the ellipsoid is less sharper compared to the four other cases. The $\alpha$ parameter decreases in the incident angle variation range of 23–23.1° with almost double rate comparing to the range of 22.9–23° while the shape spacing is uniformly increasing during the user-induced misalignments, as shown in Figure 3. The shape spacing variation behavior is related to the output CPA beam phase shift, which presents a uniform increase in the presence of incident angle variation. The highest shape spacing value corresponds to the highest beam phase shift for the case of 23.1° grating incident angle. At $(4/5)\pi$ phase shift, corresponding to the 23° grating incident angle, the shapes present a linear distribution oriented closer to the horizontal comparing to the other four cases. In the cases of $(3/4)\pi$ and $(5/6)\pi$ phase shift which correspond to the grating incident angle of 22.95° and 23.05° respectively, the linear shapes distribution present an opposite orientation related to the vertical axis. This is the result of the phase shift influence on the period and unit size of the shapes offering the possibility of controlling the design of micro and nano-patterning structures.

4. CONCLUSIONS

We demonstrated that uncompensated spatio-temporal distortions after the single-grating CPA chain in presence of user-induced misalignments (i.e. grating incident angle variation) result in a high order spectral modulation on the laser beam profile which influences the interference pattern distribution in case of multiple CPA beam overlapping. Thus, it can be used as an alternative on-site method of controlling the interference pattern distribution based on multiple CPA laser beams. The system can be easily configured to a larger number of beams.

The method presented here opens the perspective of performing a variety of interference patterns design by controlling only one parameter in the CPA optical system. The major advantage of this interference patterning method comparing to the classical lithographical femtosecond laser structuring using defined masks is the high-flexibility of controlling the structures details such as: shapes rotation angle, shapes spacing and shape structures.

This effect relates that stretcher-compressor alignment has certain limitations and it can be used to control the spatial distortions in order to improve the quality of the CPA beam profile for ultra-fast micro and nano-lithography experiments.

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