AN ALTERNATIVE METHOD FOR THE COMPENSATION OF LASER BEAM SPATIAL DISTORTIONS BASED ON COMPUTER GENERATED HOLOGRAMS

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Abstract. A fast and accurate method for the compensation of spatial distortions of the laser beam intensity profiles based on computer generated holograms (CGHs) is presented. Considering the optical beam path from a CW laser source, we simulated the aberrated intensity distribution in case of user-induced misalignments in the optical setup using a numerical ray-tracing model. To correct this aberrated intensity profile, an iterative code based on the Gerchberg-Saxton algorithm (GSA) was used to design CGHs which will be addressed on a spatial light modulator. In order to experimentally verify our numerical intensity profile correction method, two cases were investigated: the correction of the distorted intensity distribution with the aim to improve the laser beam spot profile and the achievement of a desired diffraction intensity pattern in a logo. For both cases, a specific optical setup based on two spatial light modulators was built. The results are relevant for different applications with needs of high quality laser beam profile.

Key words: spatial light modulator, computer generated holograms, spatial distortions correction.

1. INTRODUCTION

Spatial light modulators (SLM) have been successfully used in the last years as efficient tools for light properties modulation. Nowadays, their applicability increased the attention in many research areas such as: holographic optical tweezers [1,2], temporal and spatial beam shaping [3] and wavefront correction [4].

The biggest advantage of SLM is that it can be used as a wavefront sensor and compensator as well [5,6]. Many optical devices use computer generated holograms (CGHs), which represent programmable phase distributions being addressed to SLMs, in order to shape a laser beam into a defined intensity pattern in only one shot. The generation of a desired diffraction pattern using adaptive optical setups presents a great interest in several research topics such as: the creation of optical vortex [7], multiple focalization [8], beam steering [9], ultra-fast
micro-processing [10], image processing and analysis [11,12]. Due to the actual needs for fast and high laser fields, the manufacturers are now offering new and improved models of SLM devices with higher fluence threshold values.

In the ultrafast lasers domain, one of the most important applications of SLMs devices is the laser micro-machining with needs of high quality laser beam profile with no spatio-temporal distortions and simultaneous processing. In order to achieve these requirements adaptive optics is used [13, 14]. Moreover, it has been shown that adaptive optics is used as well as accurate tools to focus the ultrafast and ultra-intense laser beams on millimetre scale target in order to perform nuclear physics experiments such as photo-fission or high-energetic electrons and ions collimated beams generation [15,16].

In this paper we present an alternative correction method of the spatially distorted laser beam propagated through a user-induced optical aberrations setup being designed with Rayica software, package of MATHEMATICA. This numerically modeled setup is based on two spherical mirrors which are responsible with the spatial distortions introduced in the optical system due to a fine user-induced misalignment.

In order to show the importance of the digital holography in laser pulse wavefront correction experiments and also to correct the spatial distortions of the numerical modeled laser beam intensity profile after the user-induced distortions optical system, an experimental setup which includes two SLMs devices is used.

Firstly, we introduced numerically specific aberrations in the optical setup by varying with a very high precision the position of the spherical mirrors monitoring the effect of the user-induced misalignment on the beam intensity profile.

The aberrated intensity distributions were generated using MATHEMATICA software according to the optical path of the distorted laser beam from the CW laser system and were transferred to the first spatial light modulator from the experimental setup.

Secondly, we applied on the second SLM the computer generated holograms corresponding to each of these intensity patterns in role of the incident illumination with the aim to obtain the desired intensity distribution. The CGHs are calculated with a MATLAB code based on GSA. Thus, we created a compact and easily-implementable optical system to correct the distorted intensity profiles of the laser beam.

2. SPATIAL DISTORTIONS COMPENSATION

Broadly speaking, the beam quality can be affected by thermal distortions in the active gain media, components of poor optical quality and diffraction effects at apertures, but also by higher cavity modes and the presence of mode-hops induced-noise in semiconductor lasers [17]. Recent works relate that spatial light modulators were used efficiently as intra-cavity laser elements to compensate the laser cavity distortions [18] and dynamic holographic correctors for distortions in optical systems as well [19].
In this work, two SLMs were used to project the numerically distorted laser spot and to compensate the laser pulse distortions caused by fine user-induced misalignments in the Rayica modeled optical system.

To correct the spatial aberrations of the laser beam spot (Fig. 1), we elaborated a fast and accurate method to compensate the spatial distortions using computer generated holograms. The spatial profile of the distorted laser beam was considered as intensity distribution that has to be compensated in the experimental setup and also it is considered as an incident illumination in the CGH calculation. Two cases were investigated: when the desired output pattern is a Gaussian spatial profile or a logo pattern. The experimental setup, which was considered for the demonstration of the capability to compensate the spatial distortions using two SMLs, is shown in Fig. 2.

2.1. OPTICAL DIFFRACTION PATTERNS GENERATION SETUP

A laser diode was used as a light source with an emission spectrum centred at 650 nm followed by a telescope to enlarge the laser spot and to ensure a proper illumination of all active area of the first SLM. In our configuration both SLMs operate independently. Two computers were used to address the aberrated intensity profile on the first SLM, and the corresponding CGH to the second SLM. The first P1 polarizer generates a linearly polarized laser beam for the first SLM while the second polarizer (P2) adjusts the amplitude information conducting on the second SLM. The third polarizer adjusts the intensity on the CCD.

The SLMs are identical (LC2002 from HOLOEYE) twisted nematic liquid crystal displays from Sony Model LCX016AL, with 26.6×20 mm active area, with a VGA graphic card resolution (800 columns and 600 rows active pixels), 32 µm pitch, 200:1 contrast ratio, 60 Hz image frame rate, nearly phase-only modulation, acceptable response time (~5 ms), increased fill factor. The SLM opto-mechanical properties allow us to work with high-power laser systems with intensities in the range of 1-2 W/cm² in continuous wave regime. Even huge peaks from femtosecond lasers are not critical as long as average power density is in this range.
The final images (after the second SLM) are recorded on the CCD camera (Pike F421C resolution 2048×2048, 7.4 µm pixel pitch, 75 fps) which was placed at the focal plane of the reimaging lens L3.

Fig. 2 – The experimental setup for the laser beam intensity profile correction. L1,2,3: lenses; P1,2,3: polarizers; SLM1,2: spatial light modulators; CCD: charge coupled device; CGHs: computer generated holograms addressed on the SLMs in order to correct the aberrated beam intensity profile (I) and to generate high quality logo diffraction patterns (II).

We consider as input illumination on the first SLM used in the experiment a Gaussian beam. We addressed on this SLM the images obtained in MATHEMATICA with aberrated intensity distribution presented in figure 1 and the output intensity distribution after this SLM (and the second polarizer) recorded on the CCD is in accordance (Fig. 3). The output intensity distribution obtained from it represents the incident illumination on the second SLM. On the second SLM we address specific CGH computed for two different tasks: to correct the distorted beam intensity distribution with the aim of improving the spatial profile of the laser beam spot and to achieve a desired diffraction intensity pattern in a logo.

Fig. 3 – The intensity profile of the aberrated beam according to the transmission function $t(x,y)$ in case of user-induced distortions on the laser beam profile.
The images generated in Rayica are sampled taking into account the Nyquest criterion and they become the discrete transmission function which corresponds to the experimental intensity distribution in the optical system. The discrete coordinates in the CGH plane and in the image plane are:

\[ x = m \cdot \Delta x, \quad y = n \cdot \Delta y, \]
\[ x_z = m_z \cdot \Delta x_z, \quad y_z = n_z \cdot \Delta y_z, \]

where \( n \) and \( m \) are the numbers of the pixels in \( x \) and \( y \) directions, \( \Delta x \) and \( \Delta y \) are the pixels dimensions in the CGH plane on both axes, \( n_z \) and \( m_z \) are the numbers of the pixels in \( x_z \) and \( y_z \) directions and \( \Delta x_z \) and \( \Delta y_z \) are the pixels dimensions in the image plane on both axes.

The relation between the dimensions of the pixel in the output plane and the dimensions of the pixel in the SLM plane is given in reference [20]:

\[ n \Delta x \Delta x_z = \lambda d, \quad m \Delta y \Delta y_z = \lambda d, \]

where \( d \) is the distance between the CGH plane and the image plane.

2.2. DIFFRACTIVE STRUCTURES ADDRESSED ON THE SECOND SPATIAL LIGHT MODULATOR

We apply on the first SLM the transmittance function \( t_i(x,y), \ i = 1:4, \) corresponding to the four images presented in Fig. 3. The transmittance function is a two-dimensional (600×800 intercepted pixels) distribution of 8-digit quantization of 256 gray levels. Each gray level introduces a different value of the electronically addressable potential on each pixel of the SLM and, consequently, different refractive index and phase shift in the optical path of the incident beam.

We employed a suitable scheme [21, 22] of the GSA which is implemented in MATLAB to calculate the diffractive structure being addressed on the second SLM. It simulates the backward and forward propagations between the input plane (CGH plane considered in the second SLM plane) and the output plane (image plane considered in the screen plane). We consider as input variables on the second SLM the images from Fig. 3. A Gaussian intensity profile and a logo were the desired patterns in the screen plane.

In our numerical study we allow for a complex incident wavefront. This complex plane wave (with amplitude \( A(x,y) \) and normalized phase \( \phi(x,y) \)):

\[ C(x,y) = A(x,y) \cdot \exp[i \ \pi \ \phi(x,y)], \]

incident on the second SLM was generated in two cases:

\[ \alpha) \ A(x,y) = ti(x,y) \ \text{and} \ \phi(x,y) = ti(x,y); \]
\[ \beta) \ A(x,y) = ti(x,y) \ \text{and} \ \phi(x,y) = \pi; \]

\[ i = 1:4. \]
We generated the computer holograms for each case of aberrated beam-like incident illumination; this process is iterated until the best diffraction efficiency is obtained in the screen plane. The constraints which are put at each iteration on the matrix which corresponds to CGH is to keep the amplitude constant \( A(x, y) = 1 \) and for the final matrix which correspond to the CGH that will be addressed on the second SLM, the final phase is discretized to take eight grey levels.

3. RESULTS AND DISCUSSIONS

To assess the optical correction of laser pulse aberrations, we investigated two cases in order to verify experimentally our numerical beam intensity profile correction method.

3.1. DISTORTED BEAM PROFILE CORRECTION USING GSA

To correct the distorted shape of the laser pulse intensity distribution shown in Fig. 4α and to obtain a simple Gaussian distribution after the second SLM, we start GSA considering as desired pattern in the image plane a Gaussian intensity profile and, as incident illumination, the aberrated intensity distribution. The calculated details of the CGHs illustrated in Fig. 4δ are addressed on the second SLM. These CGHs contain information in phase-only discretized in eight levels and they provide the correction of the aberrated intensity profile to the Gaussian beam.

In figure 4, the images labeled with α present the experimental intensity distributions for the case considered in Rayica introducing optical aberrations in the laser setup. These images are obtained experimentally after P2 when we address on the first SLM the final aberrated images from Rayica. The diffraction patterns of the corrected shape of the laser beam spot obtained after the second SLM are depicted in Fig. 4β. These images prove the efficiency of this method to improve the circularity of the laser beam spot. In this way, the spatially distorted beam spot after the optical system is compensated and it is ready to be used for experiments where uniformly beam spots laser pulses are needed. Thus, a considerable adjustment of the aberrated laser beam intensity distribution can be obtained, according to actual needs in terms of high quality laser beam profile for accurate and precise laser applications.
3.2. LOGO-LIKE DIFFRACTED INTENSITY DISTRIBUTION

In the context of identical experimental conditions as in previous case, our second numerical investigation has the aim to create in far field the diffraction patterns of the desired image (LOGO) after the propagation through the experimental chains. Also the simulations to obtain the CGHs are similar.

For this, we consider as input illumination on the first SLM used in the experiment a simple Gaussian beam. We addressed on it the images obtained in MATHEMATICA with aberrated intensity profiles presented in Fig. 5α. The output intensity distribution obtained from it represents the incident illumination on the second SLM, where we address specific CGHs (Fig. 5δ) computed to achieve a desired diffraction intensity pattern in a logo shape (Fig. 5β), observed by a CCD image sensor at the focal plane of L3. All the final images were recorded in the same experimental conditions.
First, we generated an image related with those represented in Fig. 5β as the desired virtual object. Secondly, we calculated the details of the corresponding CGH based on phase only information (Fig. 5δ) to reconstruct the diffraction pattern (Fig. 5β) of the desired image at the focal plane, using as input illumination the distributions from Fig. 5α.

For comparison, we used the same experimental setup and we started also with the same image (represented in Fig. 6α) as the desired virtual object and computed a CGH in situation without aberrated incident illumination (Fig. 6δ). The corresponding experimental far field intensity distribution is presented in Fig. 6β, using as input illumination a simple Gaussian beam, with no distortions.
Fig. 6 – The desired virtual object (α) and its diffraction pattern in the image plane (β) corresponding to the laser beam without spatial aberrations, together with the associated CGH (δ).

The optical aberrations correction performances for the reconstructed pattern of the laser beam profile are summarized in Figs. 7 and 8. These plots illustrate the effect of the optical aberrations on laser beam shape used in role of the input illumination in the holograms generation process. By comparing the details from Fig. 5β and Fig. 6β it is shown that the presence of optical distortions on the laser beam slightly reduces the intensity of the reconstructed pattern of the desired image. This phenomenon is explained by the influence of the spatial distortions on the intensity distribution of the laser beam wavefront which alters the circular shape of the incident beam spot. All polarizers were rotated to obtain the maximum intensity on the screen.

Thus, we analyzed the differences between the aspects in terms of optical intensity and pixels density of the diffraction images (Figs. 5β and 6β for all four cases of spatial aberrations on the laser beam profile) before and after the laser beam propagation through the user-induced optical distortions setup.

These differences were calculated from the evolution of the pixels gray values (Fig. 7) and black pixels cumulative area (Fig. 8) registered in the red channel respectively binary mask configuration of the diffraction images, with respect to the optical aberrated beam before and after the propagation through the user-induced optical distortions setup.

Applying this fast GSA-based method in order to generate the diffraction pattern of a desired image brings an important correction effect on the distorted beam intensity profile caused by the optical aberrations. As it can be seen in figure...
7, the difference between the maximum and the minimum pixels gray values of the diffraction patterns obtained in both cases with and without spatial distortions is in range of 5 to 5.5 %, taking into account the possibly fluctuation of the light source intensity between the times the reference and sample measurements are made. These effects occur due to different factors such as superposition of the diffracted orders when the adjacent diffractive orders are very closed spaced, non-collimated diffracted beams, optical noise due to a very high background radiation and the critical adjacent polarizers alignment.

In order to evaluate the imaging quality resulted from the GSA-based method, the cumulative area of black pixels with value of 255 was analyzed on the binary mask configuration of the diffraction patterns. The cumulative area characterizes the scaling properties of the black pixels registered in the diffraction plane for all cases previously investigated. The results illustrated in Fig. 8 give the information of the total amount of optical information registered in the binary mask of the diffraction patterns as black pixels with respect to the optical aberrated beam before and after the propagation through the user-induced optical distortions setup.
The efficiency of the GSA-based method used to generate the diffraction patterns is given by the difference between the values of the cumulative area of black pixels registered before and after the user-induced optical distortions setup. Considering as reference the value of the cumulative area of black pixels measured in case of no spatial distortions, we obtained a diffraction optical reconstruction efficiency of approximately 75%.

![Cumulative Area of Black Pixels](image)

Fig. 8 – Black pixels cumulative area registered in the binary mask of the diffraction patterns of the desired image reconstructed with the laser beam before and after the propagation through the user-induced distortions system.

These results are relevant for our present study and they prove that our laser beam intensity profile correction method offers the possibility to achieve high quality diffraction patterns.

4. CONCLUSIONS

In this paper we have experimentally demonstrated the correction of the spatially distorted beam shape resulted after the user-induced optical aberrations setup using two spatial light modulators. For this, we considered the numerically modeled optical system in Rayica and we addressed on the second SLM the associate CGHs, computed with a given incident illumination containing specific spatial distortions in case of fine misalignment of the optical system. The CGHs were calculated using GSA algorithm based on an iterative code.
The final results demonstrate that spatially distorted beam shapes can be adjusted and high quality diffraction images can be achieved employing such fast and effective correction procedure. Also, it was shown that this accurate method maintains the optical intensity of the diffraction images pixels on high level during the reconstruction process and it provides good diffraction optical reconstruction efficiency due to the computational generation of the CGHs using GSA code. According to the final results, we conclude that our proposed beam intensity distribution correction method was successfully implemented in both cases investigated in this paper.

This method is ready to be implemented in our laboratory in order to compensate the spatial distortions of the pulse during the propagation through CW laser systems with spatial aberrations and to generate high quality desired patterns for achromatic imaging system with needs of full laser beam shaping control.

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REFERENCES