Design of a phase shifting interferometer in the EUV for high precision metrology

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Abstract. We present the design of phase shift interferometer for the extreme ultraviolet (EUV) that will be used with the illumination provided by a table top Ne-like Ar laser emitting at 46.9 nm. We develop a model that computes the beam propagation through the instrument, taking into account the influence of the fluctuations from shot-to-shot of the pulsed EUV laser on the retrieved wavefront.

1. Introduction

The development of compact light sources with wavelengths in the extreme ultraviolet (EUV), covering the range of 10 to 50nm [1], has favoured the research in a large number of applications such as the characterization and processing of materials [2, 3], the techniques for high resolution metrology [4-8], the studies in atomic physics, photochemistry and photo physics [9,10], the biological imaging [11,12], the diagnosis of very high-density plasmas [13,14], the study of nonlinear phenomena [15], and even integrated circuit lithography [16].

High precision metrology at short wavelengths offers extended resolution as compared with the visible range. Although coherent sources emitting in the EUV allow performing interferometry at that range, the implementation of this technique is complicated due to the lack of high efficiency refractive or reflective optics. Several architectures, such as shear [17], Lloyd [18] and point-diffraction [4] interferometers, are suitable for EUV illumination. Nevertheless, the techniques that use a single interferogram, although very effective in some cases, have several limitations. Phase shifting interferometry (PSI) is a well-established measuring technique in optical testing [19,20]. Using several interferograms, the phase of the wavefront can be retrieved at each point in the space domain regardless of the neighbouring points by a simple mathematical calculation.

Medecki developed a PSI compatible with EUV light illumination [5-7]. This interferometer is based on the point diffraction interferometer (PDI), adding the ability to implement the phase shifting algorithm, and consequently increasing significantly the performance of the interferometer. In Medecki’s interferometer, the accuracy of the reference beam is better than $\lambda_{\text{EUV}}/357$ (0.038nm for 13.5nm within a numerical aperture (NA) of 0.082) [8]. Despite this, the PS/PDI is susceptible to light scattering in the optics under test, producing misleading interpretations of the results. Furthermore the...
architecture of this device results in a large amount of tilt and coma, which appears as a systematic error in the measurements [8].

In this article we present the design of a EUV PSI device. The design is based on a beam propagation code that takes into account the main characteristics of the optical system as well as the source utilized for illumination, in our case a compact EUV laser. A wavefront phase distribution produced by a test object is evaluated using the four step phase shifting algorithm.

The illumination source considered in this design is a table top capillary discharge EUV laser developed at Colorado State University. This source produces an intense beam at \( \lambda = 46.9\text{nm} \) with pulses of approximately 400\( \mu \)J at repetition rates up to 4Hz [21,22]. A coherence radius of 550\( \mu \)m at 1.5m from the source is obtained for a 36cm-long gain medium. The laser has a narrow spectral bandwidth, \( \Delta \lambda / \lambda \leq 10^{-4} \), corresponding to a temporal coherence length of 470\( \mu \)m. This laser is the highest average power compact coherent EUV source presently available at this wavelength.

The implementation of an interferometer with 46.9nm illumination would provide a high precision metrology tool. However, since this laser is pulsed it is necessary to evaluate the influence of the possible pointing instabilities in a PSI setup. We study the influence of the laser pointing fluctuations in the phase retrieving.

The paper is organized as follows: in section 2 we describe the design of the interferometer and the choice of its components. In section 3, we analyze the performance of the interferometer as a function of the laser fluctuations by numerical simulations, to this end a Gaussian beam propagation model is employed. Finally, the conclusions are presented in section 4.

2. Description of the interferometer

Several aspects have to be taken into account when designing a phase shift EUV interferometer. First, due to the high absorption in materials at EUV wavelengths it is necessary to use diffractive and reflective optics in the experimental setup instead of the conventional refractive optics. Second, when implementing the PSI technique to measure a sample with high accuracy (of the order of a fraction of the wavelength), it is preferred that the wavefronts of the interfering beams are to be as similar as possible. Since interferometry is a comparative subtractive technique, it is desirable that the obtained phase difference corresponds to the phase introduced by the tested object, and does not include a spurious phase due to the geometry of the interferometer.

On the basis of the previous arguments, we propose the interferometer that is depicted in figure 1 in which the path beams are completely symmetrical. When considering the idealized situation, where the interferometer is perfectly aligned and the laser has full pointing stability, we observe zero fringe at the detector plane. In this situation, the beam impinges normal to the first diffraction grating \( G_1 \), that is situated at a distance \( d_o \) from the origin of coordinates. The wavefront is divided at the grating, which plays the role of a beam splitter in this set up. The first positive and negative diffraction orders (1 and -1) define the two arms of the interferometer. The zero diffraction order and higher orders are blocked. The angles at which the order 1 (\( \theta_1^+ \)) and the order -1 (\( \theta_1^- \)) are diffracted, are symmetrical with respect to the \( z \) axis, and are defined by the grating equation \( \sin(\theta_n^+) = \mp \lambda / p \), where \( \lambda \) is the wavelength and \( p \) is the period of the diffraction grating.

The beams propagate until they impinge on the mirrors, which are located at half way between the two gratings. The two mirrors redirect the beams in such a way that the incidence angle on the second grating \( G_2 \) is minus the diffraction angle produced by the first grating \( G_1 \). So, if the order +1 is diffracted by \( G_1 \) with an angle \( \theta_1^+ \), then the incidence angle onto \( G_2 \) is \( -\theta_1^- \). In this way, the order +1 diffracted by \( G_2 \), emerges from the interferometer with an angle equal to zero. In a similar way, if the order -1 is diffracted by \( G_1 \) with an angle \( \theta_1^- \), then the incidence angle in \( G_2 \) is \( -\theta_1^- \). Consequently, the two beams emerge from the interferometer with a diffraction angle equal to zero, and they are recombined like in a Mach-Zhender interferometer. The detector is situated at a distance \( d_{CCD} \) from the second grating as it is shown in figure 1.
With the aim of considering a more realistic scenario, two optical devices are incorporated. One is a telescope that is used to expand and collimate the incident beam on the interferometer, and the other is an imaging system which allows focusing the plane, where is placed the object under study, on the detector.

The purpose of using the telescope is to get a more uniform beam with a smaller divergence. The telescope is situated at the entrance of the interferometer and can be set in different ways, according to what kind of optics is intended to use. Then, two Schwarzschild objectives, two curve mirrors or two zone plates can be employed. In order to simulate the effect of these elements we will suppose that the telescope magnification is 50X.

We assume that the object under study is placed on the plane of one of the mirrors used to deflect the laser beam, for example the mirror \( E_1 \) of the test arm. Thus, in order to evaluate correctly the wavefront distortion in that position it is necessary to use an imaging system that focuses the mirror plane on the camera. Instead of introducing complicated calculations to model exactly this optical system, which is not the aim of this work, we simplify the process to obtain the phase introduced by the object under study in the coordinates where it is located, first calculating the field distribution just after the second grating and then we reverse propagate the field distribution over a length corresponding to the position in which the object is located.

In the interferometer studied here, the controllable phase shifts required by the PSI technique are obtained by moving a grating transversally to the grooves. This allows moving a component in the interferometer keeping fixed the distances between other components, and is more stable in the alignment of the device. Since the laser we are considering for the design of the interferometer is pulsed, the most appropriate class of phase retrieving algorithms is that one that introduces discrete phase shifts (one shift for each pulse), this are usually referred as bucket techniques \[20\]. Although the precision in the phase recovery process usually improves as the number of interferograms increases, the lack of pointing stability in the incident laser beam contributes to the addition of noise for each extra interferogram. Then, to establish a trade off between the number of interferograms and the introduced noise we choose the four step algorithm. The intensity distribution for the interferogram corresponding to the \( n \) step is written as

\[
I_n(x) = I_0(x)[1 + \nu(x)\cos(\Omega(x) + \delta_n)]
\]  

(1)

where \( \delta_n \) is the introduced discrete phase shift \( n \), \( I_0(x) \) is the incoherent sum of the intensities of the two interfering beams, \( \nu(x) \) is the contrast and \( \Omega(x) \) is the unknown phase difference. In this

**Figure 1:** Schematic of the interferometer and beam path in perfect alignment conditions and perfect pointing stability. The gratings \( G_1 \) and \( G_2 \) are used as beam splitters. The mirrors \( E_1 \) and \( E_2 \) redirect the beams to impinge at the correct angle on \( G_2 \).
algorithm, the phase shifts $\delta_n$ are 0, $\pi/2$ and $3\pi/2$, so the four corresponding intensities are obtained by the substitution of this values in equation (1). Operating with the four intensities, it is possible to get the spatial phase distribution in modulus $2\pi$

$$\Omega(\vec{x}) = \tan^{-1} \left[ \frac{I_4(\vec{x}) - I_2(\vec{x})}{I_1(\vec{x}) - I_3(\vec{x})} \right]$$

(2)

The most common error sources when implementing the PSI technique, are largely analyzed in the literature [20]. Nevertheless an error analysis due to pointing instabilities in the incident beam has not been yet done, since in general, continuous wave stabilized lasers with high pointing stability are used as illumination source. Since those are not the characteristics that EUV laser, it is interesting to analyze what are the tolerances on these parameters that allow to retrieve the phase accurately.

3. Numerical simulation and analysis of the phase measurements

In this section we present a study about the feasibility of using the proposed interferometer with an illumination source with the characteristics of the mentioned EUV laser. To do this, we have performed numerical simulations of the interferometric process, taking into account the features of the laser and the interferometer. The numerical experiment consists in the evaluation of the wavefront produced by a fictitious object.

The analysis was carried on by calculating analytically the intensity distribution at the detector and the retrieved phase, as a function of the parameters that constitute the interferometer and the laser fluctuations. To this end, first we have simulated the propagation of the beam through the interferometer using the Gaussian beam model. Although the transversal intensity distribution of the laser is a donut mode, its overall behaviour (collimation, divergence, and transverse size) is governed by the lower order Gaussian beam mode (TEM$_{oo}$) while the structure of the intensity distribution is preserved during propagation as a donut profile. Consequently, we used the TEM$_{oo}$ mode to have a first approximation of the results, keeping in mind that the goal of this simulation is to find an analytical expression that allows us to calculate the propagation of the beam in the interferometer and to obtain analytical expressions for the interference patterns.

We employed the Kirchhoff integral, in the Fresnel approximation, to describe the free propagation of the beams between the different elements of the interferometer. The distances that the beams propagate, i.e. the optical paths, were calculated by using geometric analysis of their trajectories and the effect of the gratings and mirrors were expressed in the Gaussian beam formalism, according to the model developed by Martinez [23] for calculating the transmission of beams by elements of finite size.

In order to take into account the fluctuations in the laser parameters we supposed the general case in which the incidence angle ($\gamma$) on the grating $G_i$ and the displacement of the emission axis ($x_o,y_o$) associated with different pulses fluctuate around their zero mean values (that correspond to the case of full pointing stability described above). Since each interferogram is obtained with a different laser pulse, it is required to know exactly the dependence of the optical paths lengths on the fluctuating parameters.

The simulations of the measurements were performed using the object sketched in figure 2. This object consists in a wedge that forms an angle $\phi$ with respect to a plane (see figure 2); this plane could be directly one of the mirrors used in the interferometer, such as the mirror $E_1$ of figure 1, or a surface parallel to it. The other mirror of the interferometer ($E_2$), is a reference surface. The choice of this object, which ideally would introduce a linear phase, was due to two main reasons: on one hand, expressing a linear phase in the Gaussian beams formalism is more simple. On the other hand, it facilitates the analysis of errors associated with spurious phases.

In order to have a phase difference between the two beams near zero, the plane on which the wedge is placed, should be set parallel to the reference mirror $E_i$. Thus, in the ideal case, where there were
not problems of pointing stability and under a perfect alignment of the interferometer, no fringes should be observed in the region corresponding to the reference plane, while equally spaced straight fringes should appear in the region corresponding to the wedge. Once the phase is retrieved, after measuring the four interferograms, the wavefront introduced by this object should be properly reconstructed. If, however, fluctuations in the direction of the laser happen to be present, this reconstruction will no longer correspond to two perfect plane mirrors that form an angle $\varphi$ between them, resulting in misleading measurements.

**Figure 2**: Scheme of the object utilized to evaluate the stability of the phase recovery process, when there are random fluctuations in the incident beam. The object is composed by a wedge located on a plane surface, parallel to one of the mirrors that constitute the interferometer.

In the case that there are pointing instabilities, the interference pattern obtained by the pulse $n$ and a phase shift $\delta_n$ will have associated a set of laser fluctuation parameters, indicated as $\{x_{an}, y_{an}, \gamma_n\}$. Then, each intensity distribution necessary for the implementation of the algorithm in equation (2) will be defined as: $I_n(\vec{x}) = I(\vec{x}, \{x_{an}, y_{an}, \gamma_n\}, d_o, G, z, \varphi, \delta, \omega)$, where we explicitly show the dependence on the parameters. As a consequence, the phase difference between the two arms of the interferometer depends on the fluctuating parameters through the four intensities and the algorithm as $\Omega(\vec{x}) = \Omega(\vec{x}, \{x_{an}, y_{an}, \gamma_n\}, d_o, G, z, \varphi, \omega)$. From now and on, in order to simplify the notation, the set of 12 parameters corresponding to the four laser pulses used for the implementation of the algorithm will be denoted with the letter $\eta$, and so $\eta = \{x_{an}, y_{an}, \gamma_n\}_{n=1,4}$. Thus the phase distribution will be noted as $\Omega_{\varphi,\eta}(\vec{x}) = \Omega(\vec{x}, \eta, d_o, G, z, \varphi, \omega)$.

The retrieved phase was calculated by subtracting the phase produced by the wedge and the phase that corresponds to the region parallel to the mirror $E_2$. However, since the goal of this numerically simulated experience is to determine whether the phase introduced by the wedge with respect to the plane is properly recovered, it was assumed, in order to avoid edge effects, that both the plane and the wedge were extended in all points of space illuminated by the beam. That is, first we calculated for every point of the detector the phase introduced by the plane with respect to the reference mirror $E_2$, as if the wedge were not present (and then $\Omega_{\varphi=0,\eta}(\vec{x})$). Then, we did the same for an inclined plane at an angle $\varphi$, as occupying the entire object space (and then $\Omega_{\varphi,\eta}(\vec{x})$) and finally, we subtracted both phases. Then, the phase introduced by the wedge was derived from the following equation

$$R_{\varphi,\eta}(\vec{x}) = \Omega_{\varphi,\eta}(\vec{x}) - \Omega_{\varphi=0,\eta}(\vec{x}) \quad (3)$$

With the aim of evaluating the confidence of the measurements, we calculated the errors using the criterion of the root mean squared, which is a statistical quantity that represents adequately the performance measurement system, since it is an evaluation of all the area of measurement. Afterwards we studied the rms errors as a function of the tolerance of the parameters fluctuations.
In order to perform the numerical simulations, it was necessary to give some values to the construction parameters of the interferometer, which remain constant during this analysis. These values were chosen taking into account several aspects, namely: the beam area should cover most of the surface of the first grating (which maximum lateral size could be 2.5mm), the diffraction orders -1 and 1 have to be sufficiently separated in the position where they impinge on the mirrors, in such a way that the other orders can be blocked. These results in the following values: the period of the gratings $p$ was chosen to be 1000 $\mu$m, the distance between the laser and the first grating $d_0$ equaled 660mm, the distance between gratings was $G_0$~640mm, and the focal distances of the mirrors or zone plates that build up the telescope were $f_1=10mm$ and $f_2=500mm$. The distances between the telescope mirrors or zone plates, the capillary laser and the first grating, were chosen in order to keep the distance $d_0$ between the beam waist (at the capillary output) and the first grating $G_1$, fixed at a value of 660mm.

The phase functions were evaluated at $20\times10^4$ pixels, corresponding to the number of pixels on the detector that are covered by the beam. Thus, by replacing the continuous variables $x = \{x, y\}$ with the discredited versions $x_{i,j} = \{x_i, y_j\}_{i,j=1:M}$ in the expressions for the retrieved phases, we obtained the phases in matrix notation as $\Omega_{\varphi=0,\eta} = \Omega_{\varphi=0,\eta}(x_i, y_j)$, $\Omega_{\varphi,\eta}^{i,j} = \Omega_{\varphi,\eta}(x_i, y_j)$ and $R_{\varphi,\eta}^{i,j} = R_{\varphi,\eta}(x_i, y_j)$.

The rms error of the retrieved phases was calculated comparing the measurements with its expected values. In this case, the expected value is the measurement in the ideal case when there are not fluctuations in the laser beam, which corresponds to the set $\eta = \{0,0,0\}_{a=1:4}$ and will be designated with the subscript $p$. For example, the error in the reconstruction phase $\Omega_{\varphi,\eta}^{i,j}$ for a wedge tilted by $\varphi$, is calculated from the root mean squared of the deviation of the measurement form the ideal case as

$$\zeta_{\Omega_{\varphi,\eta}} = \left( \frac{\sum_{i,j} (\Omega_{\varphi,\eta}^{i,j} - \Omega_{\varphi,\eta}^{i,j})^2}{N} \right)^{1/2}$$

(4)

In order to analyze the behavior of the absolute error $\zeta_{\Omega_{\varphi,\eta}}$ as a function of the tolerance for fluctuations in the beam direction due to a pointing stability $\Delta\gamma$ and fluctuations in the emission axis $\Delta\chi$, we supposed that the wedge is tilted an angle $\varphi = 5 \times 10^{-6}\text{rad}$ from the reference surface, which gives rise to three to four fringes in the interferogram.

Since the laser fluctuations are a random phenomena, to simulate the different pulses we generated random numbers for each parameter of the set $\eta$ within the tolerance interval. Thus, in order to analyze the error associated with each range of tolerance, we made a statistical study of the retrieved phases for different sets $\eta$ within the tolerance interval. In the following figures, where the errors are plotted in terms of the tolerance, each point represents the mean value of the errors obtained and the error bar represents the dispersion of these values. Since the results are expressed in logarithmic scale, the error bars show an apparent asymmetry.

The obtained results are shown in figure 3, where the errors corresponding to the phase reconstruction of the reference plane ($\varphi = 0\text{rad}$) and those corresponding to the wedge ($\varphi = 5 \times 10^{-6}\text{rad}$) are represented. In both cases, we also analyzed the influence of the telescope described in the previous section, that is, we show the results for beam divergences $\theta = 0.005\text{rad}$ and $\theta = 0.0001\text{rad}$, the latter being for a telescope with 50X magnification. The maximum ranges of pointing stability values analyzed correspond to errors in the phase reconstruction of the order of $\lambda/10$, since larger values do not meet the accuracy requirements usually set for these kinds of interferometric measurements. As it was expected, the rms error increases as the tolerances
increase in all the cases, however, it can be seen that the device is more sensitive to fluctuations in the incident angle than in the emission axis position. On one hand, when the fluctuations are due to translations of the emission axis $x_o$, no significant differences are observed for different angles $\varphi$. The use of the expander and collimator system decreases the error by a factor of up to four orders of magnitude. On the other hand, this figure shows that for fluctuations in the incidence angle, the error in the determination of the phase corresponding to $\varphi = 0$ rad is four orders of magnitude smaller than for the tilted wedge. In the latter case, the telescopic system decreases the error by two orders of magnitude. Remembering that the plane $\varphi = 0$ rad is parallel to the mirror in the reference arm of the interferometer, it is clear that such small fluctuations in the angle of incidence increases when the laser impinge on areas that are deviated from this condition.

Since in all the cases the error in the determination of the phase corresponding to $\varphi = 0$ rad ($\Omega_{\varphi=0,\eta}$) is several orders of magnitude smaller than for the tilted wedge ($\Omega_{\varphi,\eta}$), the error in the retrieved phase ($\Omega_{\varphi,\eta}$) is approximately equal to $\Omega_{\varphi=0,\eta}$.

Finally from the phase distributions we have recovered the tilt angle of the wedge averaging over all simulated data obtained for each tolerance range, in the situations discussed throughout this paper. Figure 4 shows the data for errors in the reconstruction of the angle as a function of the tolerance for a wedge angle of $\varphi = 5 \times 10^{-6}$ rad, for the cases where it is used a telescope system or a direct illumination on the grating. Again we have analyzed the cases in which fluctuations are due to pointing instabilities ($\Delta \varphi$) and when they are due to variations in the laser emission axis ($\Delta x_o$).
As it was expected, the error increases with the increase of tolerance. For the range of the acceptable tolerances discussed previously (those that introduced errors below $\lambda/10$) the values obtained for the inclination of the wedge were correct. However, if we compare these results with those obtained in figure 4, in the case of not using an expander and collimator system, it is noted that the limit values obtained in the phase error (values close to $\lambda/10$) corresponds to errors in the tilt angle greater than or equal to the value of tilt to be measured, therefore the measurement in such cases would not be appropriate. As expected, the use of the expander and collimator system leads to the decrease of the error by several orders of magnitude, allowing the system to be more tolerable to the laser fluctuations.

4. Conclusions

In this work we proposed an interferometer suitable for working in the extreme ultraviolet and useful to implement the PSI technique. The illumination source considered in this design is a table top capillary discharge EUV laser which produces an intense beam at $\lambda=46.9$nm with pulses of approximately 400$\mu$J at repetition rates up to 4Hz. In order to choose the optics that composes the interferometer it was considered that the radiation at that wavelength is highly absorbed in almost any material. On the other hand it was taken into account that, as interferometry is a comparative subtractive technique, the phase difference between the interference beams must not contain spurious phases due to the geometry of the interferometer. The proposed two beam interferometer is composed by two gratings and two mirrors that provide completely symmetrical paths. In this device the phase shifts required for applying the PSI technique, are obtained by moving across one of the gratings. By numerical simulation we studied the influence of the pointing fluctuations that the laser beam suffers from shot to shot, on the retrieved phase. To this end we used a fictitious object composed by a plane mirror, parallel to the reference surface and a wedge which had an inclination of $\varphi = 5 \times 10^{-6}$ rad. The correct recovering of the phase introduced by this object was analyzed as a function the errors caused by fluctuations in the incidence angle and fluctuations in the positioning of the emission axis of the laser. Two different cases were studied; one corresponds to using an unexpanded laser beam and the other to employing an expander and collimator system with magnification 50X. As it was expected, for all cases we observe an increasing error as the tolerance in the fluctuating parameters is increased. In addition, we found that the device is more sensitive to fluctuations in the angle of incidence than to displacements of the emission axis. On the other hand it is confirmed that the use of the telescope produces a decrease in the errors by a factor greater than two orders of magnitude.

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