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Lensless phase-shifting point diffraction interferometer for spherical mirror measurement

Zhongming Yang[a,*], Jiantai Dou[b], Qun Yuan[b], Zhishan Gao[b]

[a] School of Information Science & Engineering and Shandong Provincial Key Laboratory of Laser Technology and Application, Shandong University, Jinan 250100, China
[b] School of Electronic and Optical Engineering, Nanjing University of Science and Technology, Xiao Lingwei Road 200, Nanjing, Jiangsu 210094,China

A R T I C L E I N F O

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A B S T R A C T

We demonstrate a lensless phase-shifting point diffraction interferometer with a tiny pinhole to measure spherical mirror surface figures. The interferograms used to reconstruct the surface figure are formed without imaging optics. Fresnel diffraction calculations with a coordinate transformation are studied as a means of reconstruction method for wavefront amplitude and phase. The Radon transform is used to determine the distance from the tiny pinhole to the CCD target, which guarantees the accuracy of the diffraction calculations. Our lensless phase-shifting point diffraction interferometer not only retains the higher measurement precision by the ideal reference wavefront, but also overcome the fabrication and mounting limitation of the imaging optics. The simulations and experiments have validated the accuracy and feasibility of the spherical mirror measurement by proposed lensless phase-shifting point diffraction interferometer.

1. Introduction

The development of lithography industry demands an ulra-high requirement on spherical and aspherical surface measurement, such as extreme ultraviolet lithography (EUV), which require spherical and aspherical mirrors with a sub-nanometer scale figure error [1]. Interferomeric methods are commonly used for surface figure measurement. Due to the limitation of surface error of the reference surface, commercial Fizeau and Twyman-Green interferometers generally can't get a precision higher than root mean square (RMS) value $\lambda/50$, where λ is the wavelength of the light source [2]. To overcome the accuracy limitation in traditional commercial interferometers, the phase shifting point diffraction interferometer (PPDI) has been developed for spherical surface figure measurement on a sub-nanometer scale, which applies a point aperture to generate a spherical wavefront as the ideal reference wavefront [3–8]. In the point diffraction interferometer with single-mode optical fibers as the point aperture, the numerical aperture of the diffracted wavefront is limited due to the fabrication limitation in sub-wavelength aperture optical fiber. We have developed a phase-shifting point diffraction interferometer that employs a tiny pinhole as point aperture. This system is developed for visible light (632.8 nm) with surface figure measurement accuracy higher than $\lambda/50$ RMS [6,7]. This system can't measure the spherical surface with high numerical aperture mainly due to the fabrication and mounting limitation of the imaging optics, which consists of some high numerical aperture optics. Thus, if we want to improve the numerical aperture of the test surface by our phase-shifting point diffraction interferometer, we need to overcome the limitation in imaging optics.

In this present study, we propose a lensless phase-shifting point diffraction interferometer (LPPDI) with a tiny pinhole for spherical mirror surface figure measurement, in which the interferograms used to reconstruct the surface figure are formed without imaging optics. Our LPPDI not only avoids the fabricating and mounting limitation of imaging optics, but also increases the measurable numerical aperture of the test surface. Fresnel diffraction calculations with a coordinate transformation are studied as a means of reconstruction method for wavefront amplitude and phase. The Radon transform is used to determine the distance from the tiny pinhole to the CCD target, an important quality that has major influence on the accuracy of the diffraction calculations. Section 2 presents the construction of our LPPDI and the Fresnel diffraction based numerical imaging process of the system. Section 3 shows the simulation of a spherical mirror figure measurement by our system. Section 4 experimentally validates the surface figure measurement process of a spherical mirror. Some concluding remarks are shown in Section 5.

2. System and principle

2.1. Modified phase-shifting point diffraction interferometer system

The system layout of the LPPDI is depicted in Fig. 1. The expanded laser beam is focused on the pinhole by a focusing lens, the transmit-

* Corresponding author.
E-mail address: zhongming.yang@sdu.edu.cn (Z. Yang).

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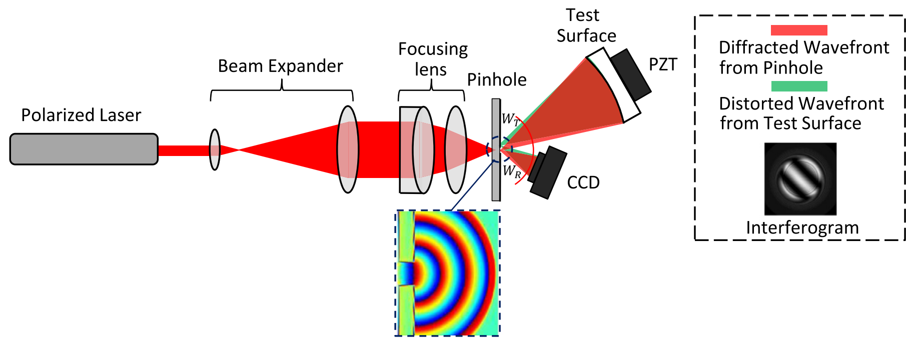

Fig. 1. System layout of the MPPDI system.

ted wave is diffracted into a nearly ideal spherical wave. The diameter of the pinhole is 1 um, which is fabricated by etching the Cr film with the focused ion-bean etching method. The diffraction spherical wave is separated into two parts: one serves as reference wave W_R, while the other serves as the test wave W_T. The test wave W_T illuminates the tested spherical surface and is reflected by it, and then reflected by the pinhole substrate, finally combines with the reference wave W_R. The test wavefront W_T and reference wavefront W_R are interfered and interferograms are formed at the CCD target. Translating the test spherical surface by a piezoelectric transducer (PZT) scanner, the surface figure error of the test surface can be measured with phase shifting method. In the typical point diffraction interferometer system, the interferogram is imaged onto the CCD target by the imaging lens [5–7]. In our LPPDI, the interferograms are formed without imaging optics, which not only avoids the fabricating and mounting limitation of imaging optics, but also increases the measurable numerical aperture of the test surface. Due to the lensless imaging, the CCD target is not the conjugated plane of the test surface, which is the exit pupil of our point diffraction interferometer, and the interferograms with edge diffraction are formed at the CCD target. So the wavefront measured by our point diffraction interferometer is different from the figure of the test mirror, and the wavefront on the test mirror must be reconstructed with the measured wavefront at the CCD target by some numerical reconstruction methods [9,10].

2.2. Numerical reconstruction process

Fig. 2 is the schematic diagram of the LPPDI system for numerical reconstruction, in which we have removed the pinhole mirror and the system has been unfolded. The complex amplitude at a point (x_1, y_1) on the test mirror is $U_1(x_1, y_1)$, which can be written as

$$U_1(x_1, y_1) = circ\left(\frac{\sqrt{x_1^2 + y_1^2}}{D}\right)\exp\left[i\frac{2\pi}{\lambda}\cdot 2\cdot \Delta W(x_1, y_1)\right] \times \exp\left[-i\frac{2\pi}{\lambda}\cdot\frac{(x_1^2 + y_1^2)}{2R}\right]\exp\left[i\frac{2\pi}{\lambda}(x_1 + y_1)\right] \quad (1)$$

where D is the clear aperture of the test mirror, R is the radius of curvature of the test mirror, $\Delta W(x_1, y_1)$ is the surface figure error of the test mirror. The test wave illuminates the tested spherical surface and is reflected by it, the phase term aroused by the surface figure error twice as the surface figure error. So, the factor in front of the surface figure error is 2. The $exp[-i\frac{2\pi}{\lambda}\cdot\frac{x_1^2+y_1^2}{2R}]$ is the spherical factor in the phase map. And $exp[i\frac{2\pi}{\lambda}(x_1 + y_1)]$ is the tilt factor in the phase map, which due to the tilt misalignment of test spherical surface [11,12]. Fresnel diffraction calculations can be used as the numerical calculation method for the complex amplitude $U_2(x_2, y_2)$ at a point (x_2, y_2) on the CCD target, which can be expressed as [13]

$$U_2(x_2, y_2) = \frac{e^{ik(R+z)}}{i\lambda(R+z)}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} U_1(x_1, y_1)\, e^{i\frac{k}{2(R+z)}\left[(x_1-x_2)^2+(y_1-y_2)^2\right]} dx_1 dy_1 \quad (2)$$

where z is the distance between pinhole and CCD target. The reference wavefront can be viewed as an ideal spherical wavefront, and the complex amplitude of the reference wavefront at a point (x_2, y_2) on the CCD target can be written as

$$U_R(x_2, y_2) = A(x_2, y_2)\exp\left[i\frac{2\pi}{\lambda}\cdot\frac{(x_2^2 + y_2^2)}{2z}\right] \quad (3)$$

where $A(x_2, y_2)$ is the amplitude of the reference wavefront. The intensity distribution at the CCD target can be expressed as

$$I(x_2, y_2) = \left[U_2(x_2, y_2) + U_R(x_2, y_2)\right]\cdot\left[U_2(x_2, y_2) + U_R(x_2, y_2)\right]^* \quad (4)$$

In our LPPDI system, based on phase-shifting algorithm, the wavefront amplitude and phase of complex amplitude $U_2(x_2, y_2)$ can be calculated by the interferograms which are registered by the CCD target. So, the wavefront on the test mirror $U_1(x_1, y_1)$ is reconstructed by Fresnel diffraction calculations, which can be written as Eq. (5). Then the surface figure profile can be got by the phase map of $U_1(x_1, y_1)$.

$$U_1(x_2, y_2) = \frac{e^{-ik(R+z)}}{-i\lambda(R+z)}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} U_2(x_1, y_1)\, e^{i\frac{k}{-2(R+z)}\left[(x_1-x_2)^2+(y_1-y_2)^2\right]} dx_1 dy_1 \quad (5)$$

2.3. Fresnel diffraction calculations with a coordinate transformation

Because of $U_2(x_2, y_2)$ is the spherically diverging wave, in the Fresnel diffraction calculation process, if we want get precise reconstruction of $U_1(x_1, y_1)$, the number of sampling on the CCD target must be increased. Due to the limited number of pixels of CCD and computational efficiency, Fresnel diffraction calculations with a coordinate transformation are chosen as a means of efficient and precise reconstruct method for wavefront amplitude and phase, which is based on Gaussian beam theory [14]. Let the origin of the coordinate system be located at the position of pinhole, which is the focus of the spherical wave $U_1(x_1, y_1)$ and $U_2(x_2, y_2)$. The coordinate transformations are given by

$$\begin{cases} x_1' = \alpha\cdot\frac{x_1}{R}, & y_1' = \alpha\cdot\frac{y_1}{R} \\ x_2' = \alpha\cdot\frac{x_2}{z}, & y_2' = \alpha\cdot\frac{y_2}{z} \\ z' = R + z = \alpha^2\cdot\frac{R+z}{R\cdot z} \end{cases} \quad (6)$$

where α is purely real, which can be chosen $\alpha = z$. By the coordinate transformation as shown in Eq. (6), transforming spherical wave $U_1(x_1, y_1)$ and $U_2(x_2, y_2)$ into equivalent collimated beam, and efficient fast Fourier transform (FFT) can be used in our diffraction calculate problem.