Optik 127 (2016) 5865–5869

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Quantitative measurement for the structure of defects on optical surface with lensless Fourier transform digital holographic microscopy

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ARTICLE INFO

Article history:
Received 27 September 2015
Accepted 6 April 2016

Keywords:
Digital holography
Holographic display
Image reconstruction techniques
Phase measurement

ABSTRACT

An effective method for detecting the structure of defects on optical surface is proposed. By integrating the lensless Fourier transform holography with digital holographic microscopy, the wave aberration induced by the defects is effectively recorded and then the accurate reconstruction result of the defect structure is obtained by using the phase subtraction method. This method will have potential application in the quantitative measurement for the defects on optical surface and is helpful for the further research and understanding the influence of surface defects on high-power laser system.

1. Introduction

In order to satisfy the requirement of inertial confinement fusion (ICF) experiment [1–3], the ICF laser driver must provide high-power and high-quality laser beam. However, the defects on optical surface, such as scratches and digs, will affect the quality of output optical field and result in the damage of optics in ICF laser driver. Therefore, quantitative measurement for the defects on optical surface with comprehensive information is significantly important for assuring the success of ICF experiment. At present, in engineering, microscopic scattering dark-field imaging technique [4–6] is used for measuring the area of the defects on optical surface. Nevertheless, the three-dimensional (3D) structure of defects can't be acquired with this method, which is disadvantageous to the further research and understanding the influence of surface defects on the high-power laser system.

For solving this problem, in this paper, a method based on lensless Fourier transform digital holographic microscopy (LFT-DHM) is proposed for measuring the 3D structure of the surface defects. By integrating the lensless Fourier transform holography [7–10] with digital holographic microscopy [11–15], the wavefront aberration induced by the defects can be well recorded and then the 3D structure of defects is calculated according to the relationship between the wavefront aberration and optical path.

Compared with other holographic recording optical geometries, such as on-axis or off-axis Fresnel holography, the advantage of using lensless Fourier transform holography is that, the high frequency information of the test sample can be more easily recorded with the limited spatial resolution of CCD target by adopting spherical wave as the reference wave [16]. Moreover, the resolution of the reconstructed image can be further improved by the use of digital holographic microscopy.

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http://dx.doi.org/10.1016/j.ijleo.2016.04.012

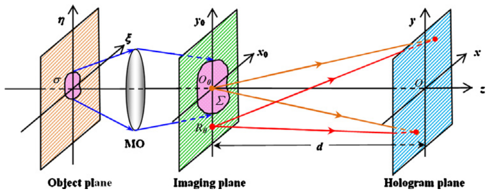

Fig. 1. Recording principle of lensless Fourier transform digital holographic microscopy.

Furthermore, the numerical reconstruction process of lensless Fourier transform hologram is very convenient, only once inverse fast Fourier transform (IFFT) operation needs to be implemented, which is available for the fast calculation of the defect structure. Considering the advantages above, the structure of surface defects is measured with lensless Fourier transform digital holographic microscopy and the effectiveness and accuracy of the proposed method is well proved by the experiment results.

2. Principles

The Recording principle of lensless Fourier transform digital holographic microscopy is shown in Fig. 1. The optical axis lies along the z direction. The object, imaging and the hologram plane are parallel and denoted by (ξ, η), (x_0, y_0) and (x, y), respectively. The points σ, O_0 and O are the centers of the three planes, respectively. The test sample $\omega(\xi, \eta)$ is magnified imaging by microscope objective (MO) and then the corresponding image $u_0\,(x_0, y_0)$ on the imaging plane is chosen as the recorded object in the holographic recording process. The reference point source R_0 is located on the imaging plane. The distance between the imaging and the hologram plane is d.

This proposed method can be decomposed into two steps. Firstly, the test sample is magnified with MO and the corresponding magnification image is obtained on the imaging plane (microscopic imaging process). Secondly, the frequency spectrum of the magnification image (rather than the test sample itself) is recorded on the hologram plane with lensless Fourier transform holography (holographic recording process). The magnification of the test sample is benefit for improving the resolution of the reconstructed image and the use of lensless Fourier transform holography is propitious to recording the high frequency information of the magnification image. The quality improvement of the reconstructed image can be well achieved by the two aspects.

According to Fresnel diffraction integral formula, the spectrum of $u_0\,(x_0, y_0)$ is recorded on the hologram plane, which can be expressed as follows

$$U\left(f_x, f_y\right) = F\left\{u_0\left(x_0, y_0\right)\exp\left[\mathrm{j}\frac{k}{2d}\left(x_0^2 + y_0^2\right)\right]\right\}_{f_x=\frac{x}{\lambda d}, f_y=\frac{y}{\lambda d}} \tag{1}$$

where, λ is the recording wavelength; k is the wave number ($k = 2\pi/\lambda$); $F\{\}$ represents the Fourier transform operation; $f_x = x/\lambda d$, $f_y = y/\lambda d$ are the transverse and longitudinal spatial frequencies in the hologram plane, respectively. Therefore, by simply implementing inverse Fourier transform operation, the complex amplitude distribution $u'(x', y')$ of the reconstructed image can be obtained.

$$u'(x', y') = F^{-1}\left\{U\left(f_x, f_y\right)\right\} = u_0\left(x', y'\right)\exp\left[\mathrm{j}\frac{k}{2d}\left(x'^2 + y'^2\right)\right] \tag{2}$$

It can be seen that the difference between $u_0\,(x_0, y_0)$ and $u'(x', y')$ is a quadratic phase factor $\exp[\mathrm{j}k(x'^2 + y'^2)/2d]$. In addition, extra phase field curvature will be induced by MO during the microscopic imaging process, which will result in the phase difference between the test sample $\omega(\xi, \eta)$ and its image $u_0\,(x_0, y_0)$. Both of the phase difference should be corrected in order to get the accurate phase distribution of the test sample and it can be conveniently achieved by using the phase-subtraction method. Assuming that the complex amplitude distributions of the reconstructed image obtained with and without test sample are $u_1'(x', y')$ and $u_2'(x', y')$ respectively, the accurate phase distribution $\varphi(x', y')$ of the test sample can be acquired as follows

$$\phi\left(x', y'\right) = \arctan\left(\frac{u_1\left(x', y'\right)}{u_2\left(x', y'\right)}\right) \tag{3}$$

Then the structure ΔL of defects on optical surface can be calculated according to the relationship between the wavefront aberration and optical path

$$\Delta L(x', y') = \frac{\Delta\phi(x', y')\lambda}{2\pi(n-1)} \tag{4}$$

where, $\Delta\varphi(x', y')$ is the wavefront aberration caused by the surface defects and n is the refractive index of the test sample.