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Fizeau interferometer with binary phase Fresnel-zone plate reference for precision measurement of large convex lens

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ABSTRACT

A method of obtaining precision transmission wavefront of large convex lens interferometrically using binary Fresnel zone plate (FZP) was presented. We present the results from a set of experiments that demonstrate the accuracy, flexibility, and the simplicity of performing the FZP test. A direct comparison of the FZP measurement with results from a Fizeau interferometry method shows excellent agreement. Finally, measurement uncertainty of lens due to alignment error and FZP fabrication processes is analyzed. This resulting analysis shows less than $\lambda/10$ accuracy for measuring the transmission wavefront of a sphere lens with 31.25 m focal length and Φ410 mm clear aperture.

1. Introduction

There is a growing demand for lenses and mirrors in the optics industry, such as information and communication technology or all branches of industrial manufacturing. To ensure the performance of optical systems, the surface shape should be manufactured to an accuracy of a small fraction of a wavelength. Many optical testing methods were developed to guide the fabrication of optical surface accurately [1-5].

Convex spherical lens is commonly measured with matching concave mirrors [6-8], fringes of interference show the shape difference between the two parts. The obvious difficulty with this method is the requirement of making and measuring a concave reference mirror. Moreover, it's virtually impossible to use this method to measure wavefront of lens with long focal length, such as tens of meters long, for air turbulence induced error and laboratory spatial problem cannot be ignored. However, holographic test could solve this problem simply. In addition, aberrations such as spherical departure of the lens can be compensated by diffraction from a circular computer-generated hologram (CGH) or Fresnel zone plate (FZP) [9-12], which is fabricated onto a flat surface.

Fresnel zone plate (FZP), a diffractive equivalent to a reflecting sphere, is a powerful tool for a whole range of alignment and calibration issues in interferometry and diffractive optics in general [13,14]. It is a special case of a CGH. The pattern on a FZP determines whether the wavefront is split into a number of beams, compensates for some aberrations in an optical assembly, or performs other useful optical functions. This high degree of flexibility in creating wavefronts of light with desired amplitudes and phases has made FZP extremely useful. A properly designed FZP can perform the functions of a conventional lens or mirror.

Diffractive optics has been used for years in optical testing [15–18] and is on its way to become an established technique. With the steady development of fabrication techniques for computer generated hologram (CGH), such as laser direct writing, e-beam writing and ion-beam writing [19-23] that provide both high accuracy and high resolution, this elegant way of controlling light has become widely accepted.

In this paper, lens transmission wavefront (TWF) measurement using FZP method is explicitly introduced, and a large zone plate over Φ410 mm aperture was fabricated with very high precision. Both theoretical analysis and experiment result show that the precision of this method is better than $\lambda/10$ ($\lambda = 632.8$ nm). Compared with Fizeau interferometry method for sphere surface testing method, the FZP method can be effectively applied to the transmission wavefront of lens with long focal length, for the configuration is very simple and compact, which is very easy to be adjusted, thus enable to obtain high precision.

2. Metrology

2.1. System construction

Traditionally, the compensation method is used to measure the transmission wavefront of large convex lens with aberration, as shown in Fig. 1. Spherical wave from an interferometer is transmitted through a compensation lens and the lens under test successively, the output parallel light is retroreflected by a reference flat.

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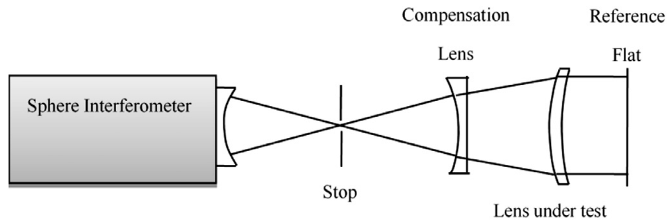

Fig. 1. Experimental setup for measuring wavefront of lens under test using the compensation method.

The testing optical system of the FZP method is composed of a phase-shifting interferometer (PSI), lens under test and a FZP, as shown in Fig. 2.

When performing a lens TWF test, FZP is equivalent to a convex mirror. Part of the collimated light from the PSI is reflected from the transmission flat (TF), forming the reference beam; the rest transmits through the TF and lens, then is retroreflected from the zone plate, and finally into the interferometer, forming the test beam. From the interference fringe, lens TWF can be obtained.

A precise characterization of the lens TWF should separate the contribution of the error in FZP substrate flatness. Measuring the substrate before the hologram pattern is generated has two main problems: one is the repositioning issue and the second, worse problem is the unknown substrate figure change introduced by the FZP fabrication process. When we subtract the nonzero-order surface measurement from the zero-order measurement, the FZP substrate error can be totally removed, leaving the residual wavefront errors from the fabrication non-uniformities. Thus, in this paper we adopt the method of measuring the zeroth order diffraction from FZP to account for substrate irregularities. In the zeroth order, the hologram emulates a flat mirror, when it is put behind the TF, the reflection interference wavefront is the reflected zeroth order wavefront of FZP. The measurement procedure of lens TWF is as follow:

(1) Measure the reflected zeroth order wavefront of the FZP.
(2) Put in lens, leaving a lens-to-FZP spacing τ the designed value. Keep the position of FZP unchanged and adjust the lens until the interferogram turns into null fringe, the obtained wavefront is the first-order wavefront. Lens TWF due to fabrication error can be obtained through subtracting the zeroth order wavefront from the first-order wavefront. But be warned, pixel matching by superposing edge feature on interferogram should be carried out, since rays propagating to FZP is convergent, as shown in Fig. 2.

Note that the lens-to-FZP spacing τ should be chosen reasonable. It is desirable to minimize the airspace τ in order to minimize the amount of atmosphere traversed by the test beam, and at the same time leave enough room for hands and for maneuvering of mounts.

The advantages of using a reflective FZP to replace a spherical mirror are threefold. First and foremost, the Fresnel-zone plate consists of nothing more than a circular binary amplitude grating. Hence, it is very easily manufactured with optical lithography. Lithographic writing is possible with $\pm 0.5\,\mu$m positioning error, offering immediate precision enhancement to the spherical shape this element represents in diffraction. Whereas use of a spherical mirror is more costly and time consuming.

The second benefit is the almost arbitrary wavefront generation. The hologram can be designed such that all rays incident on the surface are reflected back via the same path they came from, i.e., the test wave of the interferometer makes a normal incidence angle with the reflective hologram surface and is retroreflected. In this case, the interferogram only shows the deviation of the surface under test from the design prescription. Thus, it can be seen that the FZP can be powerful tools for reducing the number of elements in a setup, thereby enhancing system performance. However, when adopting the traditional compensation method, this null test requires the use of some auxiliary optics to match the *f*-number and to compensate system aberration, which therefore introduces unwanted error into the test.

Thirdly, this method is especially beneficial to the TWF measurement of lens with long focal length, for the optical path length can be less than 1 m with proper optical design. Furthermore, the longer the focal length is, the lower the fabrication difficulty and higher fabrication precision of FZP is. On the other hand, using traditional compensation method, TWF measurement of lens with long focal length creates laboratory space problems, not to mention potential wavefront errors from air turbulence.

One in particular is originality respect to previous work done by Zhou and Burge. (1) The reflective wavefront of CGH/FZP is used in the measurement here; Whereas the transmission wavefront of CGH is used to compensate the wavefront of lens under test. (2) The size of FZP could be very large since diffraction pattern on FZP is quite simple; While in the transmission mode, the size of CGH is generally small, and complicated alignment pattern should be designed since the testing system is quite sensitive to adjusting error. (3) Homogeneity of FZP has nothing to do with the measurement accuracy; Conversely, homogeneity is one of the major measurement errors in the transmission mode, and the effect of refractive index deviation should be analyzed in detail.

2.2. Design and fabrication of FZP

The design of FZP is to determine the radii and etching depth of the band structure of concentric rings on FZP substrate.

According to diffraction principle, the radial locations for ring edges, i.e., Fresnel-zone boundaries, are the positions that give integral numbers of half-wavelength optical path differences at the center of curvature from the radius of curvature value, R. FZP possesses the lens-like characteristic, and the geometric diagram of FZP is shown in Fig. 3.

The diffraction wavefront of FZP should match the transmission wavefront of lens with aberration. Following the aplanatic principle, and via optical design software, the distance between lens and FZP, the radii of FZP, and the coefficients of the various orders phase polynomial could be varied and the system optimized to retroreflect light. The geometric diagram is shown in Fig. 4. All the parallel light coming from the TF of a PSI transmits through the lens under test to the zone plate

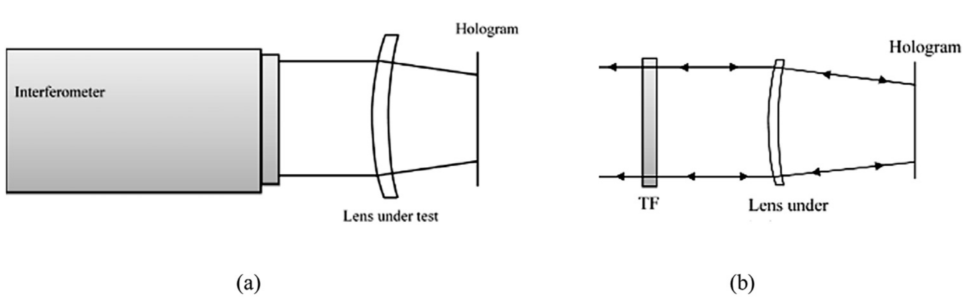

Fig. 2. Experimental setup for measuring wavefront of lens under test using FZP method.