Optics and Lasers in Engineering 88 (2017) 313–318

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

# Absolute measurement of aspheric lens with electrically tunable lens in digital holography

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ARTICLE INFO

*Keywords:*
Digital holography
Aspheric lens
Electrically tunable lens
Phase measurement

ABSTRACT

A novel method for testing aspheric lenses using digital holography with an electrically tunable lens (ETL) is proposed and experimentally verified. The ETL generates a tunable deformed wavefront which helps to decrease the high gradient of aspheric lenses. By decomposing the aspheric surface into two resolvable ones, its absolute phase can be determined using a double-exposure measurement. In this method, the wavefront generated by the ETL need not be identical to the aspheric surface as in conventional null interferometer system, but just sufficient to resolve the high gradient surface. On the other hand, the tunability of the ETL allows generation of wavefronts which can be used to test different aspheric lens. Furthermore, advantages of the ETL such as low cost, fast response, and compact configuration make the proposed method a promising technique for aspheric surface measurement.

## 1. Introduction

The performance of a high precision optical system using spherical optics is reduced by optical aberrations, and thus more optical elements are required. Using aspheric lens, these optical aberrations can be significantly reduced or even eliminated with a reduced (even single) number of optical elements [1–3]. However, testing of aspheric lenses is difficult due to high gradients on the aspheric surface resulting in high fringe densities which cannot be resolved and measured. Therefore, there is an urgent need to develop suitable test methods [4].

Many methods have been developed to measure aspheric lens. The stylus instrument is by far the most reliable tool owing to its high accuracy [5–7]. It doesn't need any null optics, nor is it influenced by the optical properties of the sample. However, being a contact method, the stylus tip could damage the optical surface. Also, the stylus tip radius smoothens the measurement like a low-pass spatial filter. Moreover, being a point-wise measurement method, it is time-consuming. The Shack-Hartmann wavefront sensor is an economical choice for the measurement of aspheric lens form [8–11]. However, the shape and pupil adaptation of the optical system is needed, and the lateral resolution of this technique is limited. In recent years, deflectometry has attracted attention as it is capable of measuring aspheric surface with simple configuration [12,13]. The main drawback of this method is that its resolution is physically limited by the projector or the grating. Interferometers with a computer generated hologram (CGH) to generate the desired wavefront have also been used [14–17]. This method has many advantages since the test and reference beams follow almost identical paths. But there is a need to redesign and manufacture new CGH for different asphere which is complicated, expensive, and time-consuming. Another interferometric method uses phase shift interferometry and heterodyne displacement interferometry to measure aspheric lens [18]. It has nanoscale vertical resolution as well as large measurement volume. However, the tested aspheric lens must be axially symmetric, have a measurable apex and defined aspheric equation, and cannot have a reversing curvature. Recently, interferometry with point source array based on structured illumination has also been proposed [19]. It evaluates the aspheric surface by fitting the spherical surface in advance. As this method does not model high-frequency components, it leads to final result containing high order systematic aberrations. Meanwhile, the calibration and alignment also greatly affect the final result.

Digital holography (DH) is a well-established high precision 3D imaging technique which is capable of numerically reconstructing the optical field of a sample at any propagation distance [20,21]. It is able to access to the intensity and phase of the sample simultaneously. Along with fast reconstruction speed, high axial resolution, and low cost, it has become a powerful tool in quantitative phase imaging. However, this technique also encounters the same high gradient problem when measuring an aspheric lens.

In this paper, a new adaptive optical element, ETL [22,23], is added

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http://dx.doi.org/10.1016/j.optlaseng.2016.09.002
Received 26 April 2016; Received in revised form 7 September 2016; Accepted 8 September 2016
Available online

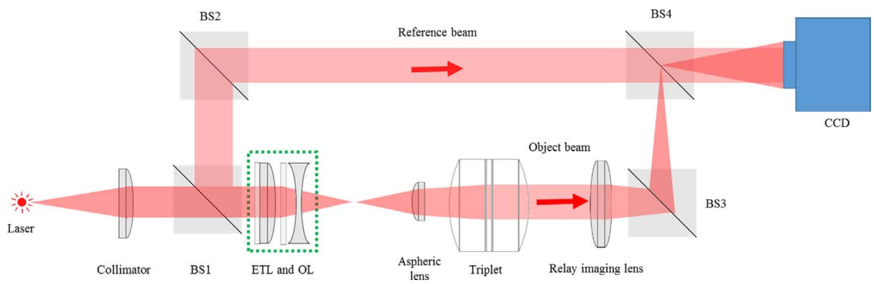


**Fig. 1.** Schematic of experimental configuration.

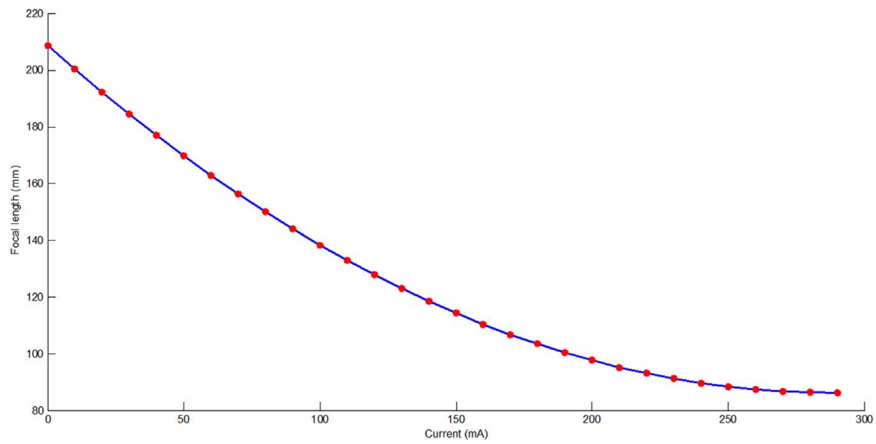


**Fig. 2.** ETL focal length variation versus driven current.

to a DH system to overcome the above problem. The electrical tuning power allows ETL to generate a suitable wavefront that decreases the high gradients of the aspheric surface. A Mach-Zehnder configuration DH system with the ETL is developed and demonstrated for the aspheric lens measurement. The experimental results are in good agreement with factory data for two sample aspheric lenses.

## 2. Methodology

### 2.1. Principle of digital holographic system

Fig. 1 shows the schematic of the Mach-Zehnder interferometer. A collimated laser beam is split by beam splitter 1 (BS1) into two beams. One beam goes through the ETL and is then normally incident on the aspheric lens surface under test. Since the beam passing through the aspheric lens diverges very fast, a triplet is introduced to reshape the beam. The other beam serves as the reference beam and interferes with object beam at BS4 with a small angular offset between them. The small angular offset is often manually adjusted to ensure the first order spectrum can be separated from the zero order spectrum in frequency domain. The image is resized by a relay imaging lens and captured by an imaging sensor which is often a charge-coupled device (CCD) camera.

The recorded image, namely, digital hologram $\mathrm{I_H}(\mathrm{x}, \mathrm{y})$ [24] is expressed as

$$I_H(x, y) = |E_O + E_R|^2 = |E_O|^2 + |E_R|^2 + E_O|E_R|\exp\{-ikx\sin\theta\} + E_O^*|E_R|\exp\{ikx\sin\theta\} \quad (1)$$

where $E_O$ is the object wave and $E_R$ is the reference wave. $|E_O|^2$ is the intensity of the object wave and $|E_R|^2$ is the intensity of the reference wave. $E_O^*$ denotes the complex conjugate of the object wave. $k=2\pi/\lambda$ is the wavenumber, and $\theta$ is the angle between the reference wave and the normal. $\lambda$ is the wavelength of the light source.

The angular spectrum method [25] is used for numerical reconstruction through a user-friendly software developed by d′Optron Pte Ltd (www.doptron.com). The optical field at a propagation distance $d$ is expressed as

$$E_O(x, y, d) = \mathfrak{I}^{-}\left\{\mathfrak{I}\left\{E_R^* I_H \exp\left[ikd\sqrt{1 - r^2}\right]\right\}\left[f_x, f_y\right]\right\}(x, y) \quad (2)$$

where $\mathfrak{I}$ and $\mathfrak{I}^{-}$ represent Fourier transform and its inverse. $f_x$ and $f_y$ represent spatial frequencies in $x$ and $y$ directions. The spatial filter radius $r$ can be written as

$$r = \sqrt{\left(\lambda f_x\right)^2 + \left(\lambda f_y\right)^2} \quad (3)$$

The phase of the object field is then obtained [26]

$$\varphi(x, y) = \tan^{-1}\frac{\mathrm{Re}[E_o(x, y, d)]}{\mathrm{Im}[E_o(x, y, d)]} \quad (4)$$

### 2.2. Numerical aperture calibration of ETL

The focal length variation of ETL (Optotune EL-10-30-C-LD) is nonlinear versus its driven current as shown in Fig. 2. Therefore, it is necessary to calibrate the ETL before any further application. The calibration is as described in our previous work [27]. Data are recorded at 10 mA steps over the working range of the ETL from 0 mA to 290 mA. The diameter of the ETL aperture is 10 mm and thus the numerical aperture (NA) of the ETL varies from 0.025 to 0.062. This is too small to compensate for the high NA of most aspheric lenses. Therefore, an offset lens (OL) is introduced to increase the NA.

The effective focal length of the ETL and offset lens can be obtained from geometric optics for two lenses in close proximity as

$$\frac{1}{f} = \frac{1}{f_{ETL}} + \frac{1}{f_{OL}} \quad (5)$$

where $f$ is the effective focal length of the combination of ETL and OL. $f_{ETL}$ and $f_{OL}$ are focal lengths of ETL and OL, respectively. In this paper, the focal length of OL is −150 mm.

The focal length of the combination is shown in Fig. 3. After