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Determining the micro-optical element surfaces profiles using transmission deflectometry with liquids

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ABSTRACT

We propose a method for simultaneously measuring the front and back surface profiles of transparent optical components. The proposed method combines dual wavelength transmission deflectometry with liquids to record distorted phases at different wavelengths, and then numerically reconstructs the three-dimensional phase information to image the front and back surfaces of the lens. We propose a theoretical model to determine the surface information, and the imaging of achromatic lenses is experimentally demonstrated. Unlike conventional transmission deflectometry, our proposed method supports direct observation of the front and back surface profiles of the optical elements. Compared with other techniques such as interferometry, the proposed setup is simpler to align, has lower cost, and does not require coherent illumination. The proposed method can be applied to normal transmission deflectometry for determining the three-dimensional surface profiles of optical components.

1. Introduction

The measurement of phase objects is a common task, and many methods have been presented over the years. Current methods can be grouped into techniques: those that (1) directly measure the wavefront and (2) measure the wavefront slope [1–3]. Interferometry falls into the first category, and provides a direct measurement of the wavefront with very high precision and resolution. However, interferometry is not suitable for measuring high curvature or large scale surfaces. The second category includes deflectometry and interferometric techniques. Deflectometry measures the deflection of reflected or transmitted light beams. The most important deflectometric methods are Moiré, Ronchi, and Shark-Hartmann methods [4–10]. Generally, these systems require a precise optical setup. However, recently, Canabal and Alonso proposed a simple technique for measuring wavefront slopes [5]. Their method consists of a liquid crystal display (LCD) monitor to generate the fringe pattern and a charge-coupled device (CCD) camera to capture the pattern distorted by the object under test. The wavefront is reconstructed after extracting the wavefront slope from the phase distributions, which are obtained by phase-shift techniques.

In transmission deflectometry and interferometry, the obtained phase includes the integrated information of the lens (bulk); i.e., we can obtain the thickness information, but not the surface information. If the lens has different curvatures of the surface, we cannot obtain the surface morphology using the normal transmission method.

The purpose of this work is to extend normal transmission deflectometry to measuring the surface profiles utilizing two illuminating wavelengths and liquids. The proposed technique involves measuring the wavefront slope of the transmission object immersed in liquid at dual wavelengths and numerically obtaining the front and back surface profiles simultaneously.

2. Dual wavelength deflectometry with liquids

Consider the optical arrangement shown in Fig. 1. The CCD camera is focused on the screen on which a periodic fringe pattern is displayed. The irradiance distribution captured by the camera, $I(x,y)$, is given by

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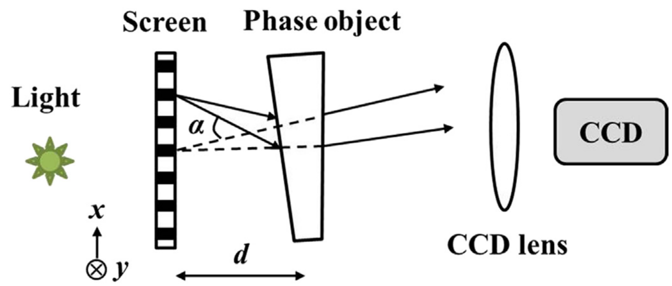

Fig. 1. Schematic diagram of deflectometry.

$$I(x,y) = I_0\left[1+\cos\left(\frac{2\pi x}{p}\right)\right], \quad (1)$$

where p is the period of fringe pattern and I_0 is the average intensity. When the phase object is positioned on the optical path, it changes the optical path length. If the phase is inhomogeneous in the x-direction, the ray will be deflected by an angle $\alpha \approx \partial K(x,y)/\partial x$, where $K(x,y)$ is the optical path length of a ray traveling through the phase object at the position (x,y). The new irradiance distribution, $I(x,y)$, is given by [11,12]

$$I(x,y) = I_0\left[1+\cos\left(\frac{2\pi x}{p}+\frac{2\pi d}{p}\frac{\partial K(x,y)}{\partial x}\right)\right]. \quad (2)$$

where d is the distance between sample and display. In Eq. (2), the deflection angle in the transmission case provides the thickness information but not shape information.

Consider the optical path difference of a beam traveling through the transparent lens (refractive index $= n_L$), immersed in liquids on either side with refractive indices n_1 and n_2, respectively (see Fig. 2). The optical path length (OPL) between planes A and B of the lens surface can be described as [13,14]

$$\begin{aligned} OPL_0 &= Z_{01}n_1 + n_L t + Z_{02}n_2 \\ OPL(x,y) &= Z_1(x,y)n_1 + L_1(x,y)n_L + n_L t + L_2(x,y)n_L + Z_2(x,y)n_2, \end{aligned} \quad \text{(3-a)}$$

$$W(x,y) = [Z_1(x,y) - Z_{01}]n_1 + [Z_2(x,y) - Z_{02}]n_2 + [L_1(x,y) + L_2(x,y)]n_L, \quad \text{(3-b)}$$

where Z_{0i} and $Z_i(x,y)$ are the vertex and surface height, respectively; $L_i(x,y)$ is the distance traveled from the surface to the vertex (i = 1, 2); and $W(x,y)$ is the path difference between OPL and OPL_0. The deviation angel depends on the $W(x,y)$. Since planes A and B are parallel, the distance between them is constant, and this determines the relationship between Z and L:

$$\begin{aligned} L_1 &= Z_{01} - Z_1(x,y) \\ L_2 &= Z_{02} - Z_2(x,y), \end{aligned} \quad (4)$$

Substituting Eq. (4) into Eq. (3-b) gives

$$W(x,y) = -L_1(x,y)n_1 - L_2(x,y)n_2 + [L_1(x,y) + L_2(x,y)]n_L. \quad (5)$$

The deflection angle caused by the phase object is given by

$$\frac{\partial W(x,y)}{\partial x} = (n_L - n_1)\frac{\partial L_1(x,y)}{\partial x} + (n_L - n_2)\frac{\partial L_2(x,y)}{\partial x}. \quad (6)$$

Eq. (6) shows that the deflection angle includes the summation over both surface profiles. Hence, we cannot measure either of the profiles using traditional deflectometry.

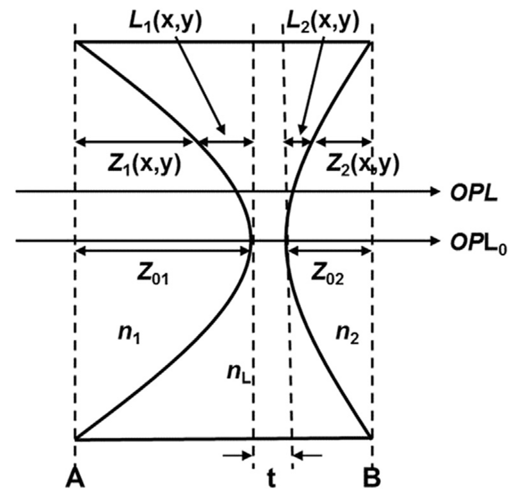

Fig. 2. Schematic diagram of a double-concave lens immersed in liquids.

However, if we could obtain a second deflection image for another wavelength, the deflection angles for two different wavelengths would be

$$\begin{aligned} \frac{\partial W_1(x,y)}{\partial x} &= (n_{L1} - n_{11})\frac{\partial L_1(x,y)}{\partial x} + (n_{L1} - n_{21})\frac{\partial L_2(x,y)z}{\partial x} \\ \frac{\partial W_2(x,y)}{\partial x} &= (n_{L2} - n_{12})\frac{\partial L_1(x,y)}{\partial x} + (n_{L2} - n_{22})\frac{\partial L_2(x,y)}{\partial x}, \end{aligned} \quad (7)$$

where $\partial W_1(x,y)/\partial x$ and $\partial W_2(x,y)/\partial x$ are the deflection angles at the different wavelengths; n_{11} and n_{12} are the refractive indices at different wavelengths of material n_1; n_{21} and n_{22} are those of material n_2; n_{L1} and n_{L2} are those of the phase object.

Eq. (7) may be written in matrix format as

$$\begin{bmatrix} \frac{\partial W_1(x,y)}{\partial x} \\ \frac{\partial W_2(x,y)}{\partial x} \end{bmatrix} = \begin{bmatrix} n_{L1} - n_{11} & n_{L1} - n_{21} \\ n_{L2} - n_{12} & n_{L2} - n_{22} \end{bmatrix} \begin{bmatrix} \frac{\partial L_1(x,y)}{\partial x} \\ \frac{\partial L_2(x,y)}{\partial x} \end{bmatrix}. \quad (8)$$

Eq. (8) shows that the shape slope information, $\partial L_1(x,y)/\partial x$ and $\partial L_2(x,y)/\partial x$, may be obtained from dual wavelength transmission deflectometry with liquids. The deflection angle, $\partial L_1(x,y)/\partial y$ and $\partial L_2(x,y)/\partial y$, may be similarly obtained.

The reconstruction shapes, L_1 and L_2, are given by integration of the partial derivatives. The literature reports several potential integration methods [15,16]. We have employed the zonal reconstruction algorithm, one of the global integration techniques, that provides optimal reconstruction of the surface profile by minimizing a cost function, which constrains the global minimization process [17,18].

3. Experimental results

Fig. 3 shows the schematic diagram of our experimental setup of dual wavelength transmission deflectometry with liquid for measuring both surfaces simultaneously. We used a CCD camera (Imperx) to record the distorted images. The pixel size and the number of pixels were 7.4 × 7.4 μm and 1024 × 1024, respectively. And we used an LCD spatial light modulator (SLM) (Holyeye LC2002) for display. The pixel pitch and the number of pixels were 32 μm and 800 × 600, respectively. Achromatic spherical lenses were used as phase objects with different radius of curvatures. Both