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Microlenses focal length measurement using Z-scan and parallel moiré deflectometry

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ABSTRACT

In this paper, a simple and accurate method based on Z-scan and parallel moiré deflectometry for measuring the focal length of microlenses is reported. A laser beam is focused by one lens and is re-collimated by another lens, and then strikes a parallel moiré deflectometer. In the presence of a microlens near the focal point of the first lens, the radius of curvature of the beam is changed; the parallel moiré fringes are formed only due to the beam divergence or convergence. The focal length of the microlens is obtained from the moiré fringe period graph without the need to know the position of the principal planes. This method is simple, more reliable, and completely automated. The implementation of the method is straightforward. Since a focused laser beam and Z-scan in free space are used, it can be employed for determining small focal lengths of small size microlenses without serious limitation on their size.

1. Introduction

In recent years, microlenses have found wide applications in various fields of science, industry, and military [1,2]. Microlenses are used both individually and as an array, in different applications such as focusing the light into optical fibers, optical fibers connection, collimation of diode lasers, high-quality imaging systems, microscopy and microsystems, spatial filtering, wavefront sensors, LCDs, etc. The most important parameters of a microlens are its focal length and its radius of curvature. Because a microlens has a small size, the determination of its focal length is not straightforward. Therefore, the measurement of the focal length of the microlens is a key factor. There are many methods for characterization of microlenses like digital holographic microscopy [3], Mach–Zehnder interferometry [4], combined Twyman–Green and Mach–Zehnder interferometry [5], interference microscopy [6], and so on [7–9]. All of the mentioned methods need expensive equipment and suffer from environmental vibrations. In addition, the interferometric testing of microlenses incurs certain difficulties due to the small sizes of the microlenses. An undesired diffraction pattern is encountered. Another problem, especially in reflection testing setups, is unwanted reflections from other surfaces than the surface to be tested. On the other hand, the Z-scan technique has been implemented for measuring the nonlinear refractive index of materials, n_2 [10]. The Z-scan technique is also used for measuring the focal length of microlenses [11]. In measuring the n_2 of materials or the focal length of a regular lens, the Z-scan technique has the disadvantage of being sensitive to the beam pointing instability and power fluctuations.

On the other hand, there are various methods for measuring the focal length of ordinary lenses, such as using the interferometry method [12], Talbot interferometry and Talbot effect [13,14], digital speckle interferometry [15], moiré deflectometry [16], Lau effect [17], and Shack–Hartman wavefront sensor [18]. All of the mentioned methods are applicable to large scale lenses.

In this paper, we have used Z-scan and parallel moiré deflectometry for measuring the focal length of microlenses. It should be mentioned that we have previously employed the parallel moiré deflectometry for measuring the atmospheric turbulence parameters [19,20] and refractive index of nonlinear materials [21]. A laser beam is focused by one lens and is re-collimated by another lens, and then strikes a parallel moiré deflectometer. In a parallel moiré deflectometer the grating vectors are parallel, and the resulting moiré fringes are also parallel to the grating lines. In the presence of a microlens near the focal point of the first lens, the radius of curvature of the beam is changed; the parallel moiré fringes are formed only due to the beam divergence or convergence. In the measuring process, the microlens is accurately shifted along the optical axis near the focal point of the first lens using a DC stepper motor. The value of the shift in a step is 1/200 mm. Then the moiré patterns corresponding to the different

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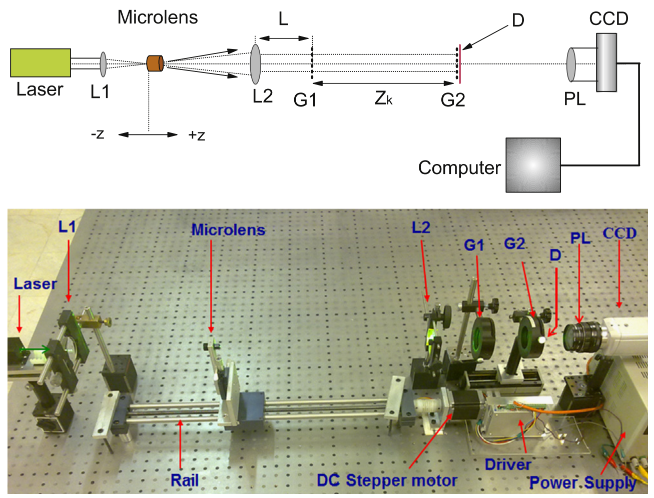

Fig. 1. Top: integrated instrument. Bottom: schematic diagram of the experimental setup. L1, L2, G1, G2, D, PL, and CCD stand for the focusing lens, collimating lens, first grating, second grating, diffuser, projection lens, and scientific camera, respectively.

positions of the microlens are recorded. In this method we measure the radius of the curvature of the laser beam as a function of the microlens position, and the focal length of the microlens is obtained from the moiré fringe period graph without the need to know the position of the principal planes. By selection of a suitable grating period and the distance between the gratings, one can adjust the precision according to the focal length of the microlens.

This method is simple, more reliable and completely automated. The implementation of the method is straightforward. Because only a focused laser beam and Z-scan information are needed, it can be employed for determining small focal lengths of small size microlenses without any limitation on their sizes.

2. Theoretical background

Schematic diagram of the experimental setup is shown in Fig. 1. After propagation through a positive lens, $L1$, the laser beam is re-collimated by the second lens, $L2$. Then the beam illuminates two gratings $G1$ and $G2$ with equal periods of d, separated by Z_k along the optical axis, in which their lines and planes are parallel with each other. The parameter Z_k denotes the kth Talbot's distance for the $G1$. The planes of the gratings are assumed to be perpendicular to the optical axis. The test microlens is placed at the focal plane of $L1$. The displacement of the microlens along the optical axis causes displacement of the location of the focus point of the beam and correspondingly changes the radius of curvature of the beam on $G1$.

In this case, the spatial period of the self-image is magnified by $(r+Z_k)/r$, where r is the radius of curvature of the laser beam at G1 plane. r is positive when the beam on the $G1$ plane is divergent and is negative when it is convergent. On the $G2$ plane, a multiplicative moiré pattern will appear by the superposition of the kth self-image of $G1$, with period $d \pm \delta d$, and $G2$, with period d, where the "+" and the "−" signs correspond to the divergent and convergent beams, respectively. In this case the spatial period of the moiré fringes obtained from [22]

$$d_m = \frac{d^2}{\delta d}, \tag{1}$$

and moiré fringes are parallel to the grating's rulings. More detail and two new applications of this kind of moiré fringes are presented in [19,21]. Using geometrical optics, it is easy to find that [19,21], $(d+\delta d)/d = (Z_k + r)/r$, and as a result one can write

$$\delta d = \frac{Z_k}{|r|} d. \tag{2}$$

Using Eq. (2) in Eq. (1) we get

$$d_m = \frac{|r| d}{Z_k}. \tag{3}$$

As shown, d_m depends on the radius of curvature of the beam.

Any change in the position of the microlens near the focal length of $L1$, causes a change in the radius of curvature of the beam and the period of moiré fringes. Now by using the ray tracing procedure [23], let us describe the propagation of the beam through $L1$ (with focal length f_1), the microlens (with an effective focal length f_{ml}), $L2$ (with focal length f_2) and the distances between the elements. By using the transfer matrices of lenses and the free spaces, the $ABCD$ matrices of the system is given by

$$\begin{pmatrix} A & C \\ B & D \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \frac{-1}{f_2} & 1 \end{pmatrix} \begin{pmatrix} 1 & f_2 - z \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{-1}{f_{ml}} & 1 \end{pmatrix} \begin{pmatrix} 1 & f_{1+z} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{-1}{f_1} & 1 \end{pmatrix}. \tag{4}$$

The effective focal length, EFL, of a system is the distance from the principal point to the focal point. The back focal length, BFL, or back focus is the distance from the vertex of the last surface of the system to the second focal point. From the theory of the $ABCD$ matrices the focal length of a system, and the EFL–BFL are given by $f_t = -1/C$, and $S = (1-A)/C$, respectively [23]. According to the configuration of the Fig. 1, radius of curvature of the beam on $G1$ is given by

$$r(z) = L - S(z) - f_t(z), \tag{5}$$

where L is the distance between $L2$ and G1 and $S(z)$ is the distance of exit plane and second principal plane of the complex optical system. After some calculations, we obtain

$$r(z) = L + \frac{f_2^2}{z} - \frac{f_{ml} f_2^2}{z^2} - f_2. \tag{6}$$

Finally combining Eqs. (6) and (3) we have

$$d_m = \left| \frac{d}{Z_k}(L - f_2) + \frac{d f_2^2}{z Z_k}\left(1 - \frac{f_{ml}}{z}\right) \right|. \tag{7}$$

According to Eq. (7) the period of moiré fringes, d_m, will be infinite, when microlense is placed at the focal point ($z=0$). By measuring the moiré fringe period at various positions of the microlens, using Eq. (7) the focal length of microlens, f_{ml}, is calculated without the need to know the position of the principal planes.

3. Experimental work

The second harmonic of a 50 mW CW diode-pumped Nd-YAG laser beam with a wavelength of 532 nm is collimated by a double lens telescopic system. The collimated and expanded laser beam strike $G1$ with the period of $d = 0.1$ mm. The second grating of the moiré deflectometer $G2$ with the same period is installed at a distance of 75 mm with respect to the first grating $G1$.

The gratings $G1$ and $G2$ are installed on suitable mounts. The holders of the gratings can be rotated around the optical axis for adjusting the angle between the grating vectors. The moiré pattern is formed at a plane where the second grating of the moiré deflectometer and a diffuser, D, are installed. Using a projection lens, PL, the moiré pattern is projected on the CCD camera.

The test microlens is installed on a micro-positioner on an optical rail and is accurately shifted along the z direction near the focal point of the first lens using a DC stepper motor. The value of the shift in a step along the z direction is 1/200 mm. It can