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Research article

High-speed, high-precision focal length measurement using double-hole mask and advanced image sensor software

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ABSTRACT

A cutting-edge precision technique for computation of focal length of a positive lens with double-hole mask is described. The technique is simple and versatile due to incorporation of the updated functions of image sensor device that supports reading the distance between beam spots instantaneously while the position of the specimen is being changed, as well as the reduction in several challenging measurement steps. Furthermore, this technique does not require prior knowledge of distances in the optical setup. High accuracy in focal-length measurement is obtained by precise beam spot distance analysis using image sensor integrated software. The acquired data exhibit considerably high precision and reproducibility.

1. Introduction

The measurement of focal lengths holds enormous practical significance in high-precision laser micromachining and 3D microprinting. This measurement contributes to better optimization of the optical lens performance associated with fabrication processes, and thus essentially impacts the working productivity of a high power laser micromachining system. A simple, high-precision, versatile optical design that does not require prior knowledge of the distances poses considerable challenges to engineers and scientists even today.

Several concepts and principles have been introduced to optimize focal length measurement. From employing the principles of geometrical optics [1,2] to using advanced optical concepts such as Moire deflectometry [3–5] and Talbot interferometry [6–11] in which the focal length is obtained through investigating the fringe pattern generated by the transmission of a collimated beam over two grating plates and lenses; grating shearing interferometry [12,13] in which the focal length is acquired by distances between interference fringes through gratings; and Fizeau interferometry [14,15] in which the focal length is measured based on the interference pattern of reflected lights from different transparent surfaces located close to each other, these techniques are all unique and distinctive in measuring the focal length of lenses. Nevertheless, there still exist considerable limitations that mainly influence accuracy of the focal length measurement associated with these concepts. First, data acquisition made with conventional CCD cameras used in methods of interferometry has associated with them errors such as spherical aberration. Second, premeasurement of optical parameters such as distances between optical elements could also lead to the uncertainty in measurement results. Finally, utilization of complicated mathematical models does it lend it to be easily applicable in industry. High precision is the most important requirement for a measurement system to evaluate the performance of sophisticated optical elements such as lenses. Practical application of methods employing Fresnel diffraction from a phase step [16] and near-field diffraction [17] with much more complicated calculations turns out to be difficult for a large number of lenses even though such methods yield high-accuracy measurement for both positive and negative lenses. A focal length measurement based on spot pattern and spherical aberration lowers the aberration effect, but leading to lower accuracy [18]. A real-time focal length determination system using a

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diffractive beam sampler (DBS) and/or CCD camera can accurately determine the focal length in case of light from a laser beam accurately through the change in the beam-spot sizes and the distances on the CCD in accordance with the relative position of specimen (S) with respect to the objective lens (OL) [19,20]. This technique can overcome the error associated with the aberration on the CCD camera owing to the pre-adjustment of the laser power during the calibration process. Furthermore, geometrical method [21] which bases shifting of image point according to shifting of object point through OL to compute its focal length, circular Dammann grating-based focal length measurement [22], differential confocal long focal length measurement [23,24], and beam spot size-based focal length measurement [25] appear to be potential techniques for computing the focal length. These methods, however, are also limited by quality of CCD camera in particular and signal detector in general. A precise and multifunctional optical design for simultaneous detection, measurement, and fabrication requires a breakthrough in technical developments and improvements.

In this research, a unique and simple method has been designed for measuring the focal length of a positive OL using a developed image sensor (IS) and double-hole mask (DHM). This technique tracks the changes in the beam-spot positions in accordance with the relative distance between the OL and S. A linear relation between the beam spots and OL—S distances can be obtained. Based on this relation, we can directly determine the ratio of the changes in beam spot positions and OL—S distances. With the enhancement, IS now can directly read the separation between beam spots automatically, based on the points of their peak intensities. The main disadvantage here is that the last CCD device can only show the beam profile, and the distance measurement is required to be carried out manually. As a result, the usage of IS can minimize the uncertainty related to images obtained by the CCD camera. The calibration process is carried out to position the single lens (SL) in front of IS for acquisition of the smallest spot sizes. Furthermore, the pre-measurement of distances between optical elements can be ignored. This system has great potential in the measurement of the focal length in optical systems. The article is organized as the following. First of all, we state the theoretical model of measurement technique which includes the geometrical optical schematic and analytical expression of focal length of a positive OL. Second, we analyze the uncertainty based on the theoretical expression of focal length withdrawn in previous section. Third, we state the experimental principle as well as the results of focal length measurement of several positive sample lenses. Eventually, discussion and conclusion are carried on to evaluate the quality as well as potential of the measurement method.

2. Theoretical analysis

In this section, the main optical design and the calculation scheme for determination of the focal length f are described. A laser beam passing through the DHM containing two small holes, which is perpendicular to the optical axis, splits into two parallel beams, passes through the OL, gets reflected on the surface of the work piece, and again passes through the OL. The beams passing through the OL are then directed to SL, which is positioned at a distance equal to the focal length of the lens from IS, by a beam splitter (BS) and then converges into IS (Fig. 1). The configuration of beam spots on IS depends on the relative position of S - a Silicon wafer acting as a perfect mirror in this experiment, with respect to the focal position. The optical elements are arranged such that the parallel beams finally converge to a point on IS as S is positioned at the focal point of the OL. Based on the ratio between the changes in beam spot spacing on IS and in distance between S and OL, the focal length of OL can be computed by pre-known parameters including distance between two holes and focal length of SL. The following calculations show the dependence of the beam spot separation on IS on defocusing the displacement of S in accordance with the principles of geometrical optics.

The parameters and symbols used in Fig. 1 are given below.

l: Distance between holes on the mask
b: Distance between I_2 and OL
c: Distance between I_3 and OL
f: Focal length of OL
f_s: Focal length of SL
ρ : The sum of IS—BS distance and BS—OL distance
u: Distance between OL and S
Δu: Defocusing displacement of S
ν : Distance between beam spots on IS
$\Delta\nu$: Change in distance between beam spots on IS
α : The angle made by laser beam and optical axis after first transmission through OL
β : The angle made by laser beam and optical axis after the second transmission through OL (reflected beam)
γ : The angle made by laser beam and optical axis after transmission through SL

According to the Fig. 1 and the description of beam path above, the intersection at point I_2 and the intersection at point I_1 are symmetric over S as perfect mirror. Thus, we acquire the following as distance between I_2 and OL:

$$b = 2u - f \tag{1}$$

Subsequently, the intersection at point I_3 is regarded as the image of the intersection at point I_2 through the OL. The position of I_3 with respect to the OL is depicted by c:

$$c = \frac{(2u - f)f}{2(f - u)} \tag{2}$$

The intersection at the point I_4 is regarded as the image of the intersection at the point I_3 through SL with the distance of $(\rho - f_s)$ between SL and OL, we have the position of I_3 with respect to the SL as $(\rho - f_s + c)$. Accordingly, p - the distance from focusing point of beams to SL is computed based on the relation of image and object through SL:

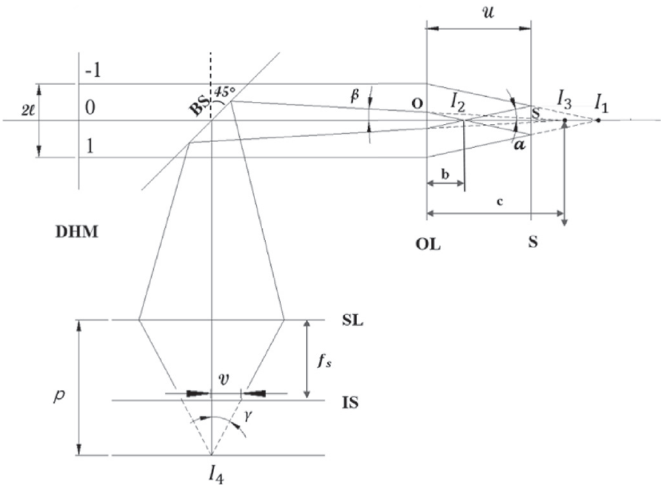

Fig. 1. The optical path of laser beam through DHM and optical setup.

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