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Measurement of focal length based on laser-beam-spot tracking system using diffractive beam sampler

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ABSTRACT

An approach for measuring the focal length of a lens using a diffractive beam sampler is presented. The high-precision measurement of the focal length is conducted while a specimen is continuously moved along the optical axis. Images of the fractional beam spots on a charge-coupled-device camera are tracked with respect to the position of the specimen to obtain the relation between the beam-spot distance and the lens–specimen distance. Accordingly, this relation can be used to infer the focal length via computation. The method is carried out by simulation, easy, and inexpensive. In addition, it is applicable to find the focal length of a thin lens as well as the effective focal length of a system of lenses because it does not require the movement or replacement of lenses. The results indicate a dramatically high precision.

1. Introduction

The measurement of the focal length has tremendous practical importance in laser micromachining and laser science. Its investigation results in the increased performance and quality of the optical lens and fabrication system and thus essentially impacts the working efficiency of a high-intensity laser. A simple, high-precision, rapid, real-time, and versatile optical system that is capable of measuring the focal length is still an enormous challenge to engineers and scientists because most of the available optical system can only carry out a single task. Several focal length measurement systems have been introduced to solve these issues.

The classical measurement of the focal length is based on image magnification through an objective lens and a nodal plane and is limited by the uncertainties in the measurement of the object and image [1,2]. Thus, the accuracy of this technique is relatively low. Moiré reflectometry [3] and Talbot interferometry [4–6] utilize a Moiré fringe and have achieved a measurement uncertainty of approximately 0.7% for a focal length of 210 mm. In these methods, the distance between two gratings is crucial and should be accurately known. The focal length is computed according to the relative lateral distance between the zero-order and diffracted first-order fringes on a charge-coupled device (CCD) camera. The aberration of the fringes on the CCD remarkably hinders the acquisition of data, thereby lowering the precision of the method to an error of 1.4% for focal lengths of 78.8 mm for a plano-convex lens and 117.4 mm for a cylindrical plano-convex lens [7]. Fizeau interferometry with a spherical mirror [8] and the use of the wavefront difference method [9] have been used to measure lenses with focal lengths ranging from −200 to 500 mm with an error smaller than 1%; however, these methods are restricted by the precise measurement of the radius of curvature, the approximate calculation of the wavefront difference, and nonparallel optical apparatuses. Confocal methods take advantage of the detection of the lens focus and the vertex of the lens surface based on an accurate distance measurement interferometer to measure the focal length, reaching a considerably high precision with an error smaller than 0.01% when measuring lenses with ultra-long focal lengths from 12 m to 50 m [10–14]. Fiber point diffraction longitudinal interferometry is affected by the uncertainty in the divergence of the beam, leading to a measurement error of about 0.4% when measuring a focal length of 25.4 mm, which is caused by the experimental environment [15]. In addition, several techniques have been presented, such as fiber-optic auto collimation [16], the reference-plate technique [17], the Hartmann–Shack technique [18], a circular Dammann grating [19], and a motion-free technique [20] which require an enhancement in the precision. A measurement technique using a spot pattern and spherical aberration considerably reduces the impact of the aberration effect on the data but has a relatively low accuracy with a relative error of nearly 1% when measuring a focal length of

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100 mm [21]. The measurement of focal length using diffraction grating provides the uncertainty of 0.09% [22]. Moreover, a real-time system for the detection of the focal point using a diffractive beam sampler (DBS) and/or CCD camera is able to identify the focal position of a laser beam precisely on the basis of the change in the beam-spot sizes and the distances on the CCD according to the relative position of the specimen with respect to the objective lens [23,24]. This technique can remove the error caused by the aberration on the CCD owing to the pre-adjustment of the laser power during the calibration process. Nevertheless, a precise and multifunctional system for detection, measurement, and fabrication requires significant technical developments and improvements.

In order to establish a new field of focal-length measurement using a simpler and more accurate optical system with a DBS, we designed a unique method for measuring the focal length using a DBS and CCD camera. This technique tracks the changes in the beam-spot distances according to the relative distance between the objective lens and the specimen. A polyline graph of the relation between the beam spots and the lens–specimen distances can be acquired. Any discontinuities can be determined along with the focal point. Thereafter, the displacement between two points will be recorded to compute the focal length by solving a cubic function with pre-known coefficients. The technique does not require the replacement or movement of lenses; thus, it can be applied to find the effective focal length of a system of lenses. In addition, the beam-spot sizes on the CCD are also examined to enhance the measurement accuracy, which is possibly reduced owing to eccentricity of the beam spots. Furthermore, an error analysis is conducted. The paper is organized as follows. First, we explain the measurement principles including, the description of an optical schematic in Section 2. Second, we analyze a mathematical model of how we acquire the expression for the focal length on the basis of the distance between the focal position and a discontinuity, and evaluate the beam -spot size on the CCD camera in Section 3. Third, we introduce our method of error calculation in Section 4. Finally, we show the experimental results when we test the measurement method with several lenses having different focal lengths, including the specifications of the optical instruments in the measurement setup.

2. Measurement principles

A focal-spot tracking system (FSTS) generally includes a DBS, silicon wafer, and beam splitter (BS), as shown in Fig. 1. The DBS is a laser-beam propagator, which can divide a single laser beam into three beams with different intensities, including a main beam and two identical fractional beams with a propagation angle α of 2.07°. The wafer is considered to be a movable specimen and is controlled by a micro-positioning system, which allows for extremely small movements in increments of 1 μm at a minimum. An objective lens (OL) is placed between the BS and the specimen. The laser beam from the source passes through the DBS and is divided into three fractional beams including the main beam (order 0) and two fractional beams (orders +1 and −1) with different intensities. Specifically, the main beam occupies about 97.5% of the total intensity, and each of fractional beams occupies about 1% of the total intensity [25]. Then, it passes through the OL, is reflected from the specimen surface, continuously passes through the OL and BS, and eventually arrives at a CCD camera. The laser-beam spot is tracked by the CCD camera. The distances and angles are indicated in Fig. 1.

In principle, we gradually move the specimen away from the OL position and track the changes in the distances between the fractional beam spots on the CCD camera. First, the distance between beam spots linearly decreases as the distance between the specimen and the OL increases. Therefore, it is obvious that there always exists a position of the specimen at which the distance between beam spots on the CCD is zero, and this is our discontinuity. From this point, the distance between beam spots on the CCD camera linearly increases as the distance between the specimen and the OL increases. During the process of tracking the laser-beam spots on the CCD, we could also detect the focal position on the basis of the technique proposed in a previous paper [23]. The focal position and discontinuity were marked, and the displacement between them was recorded to compute the focal length.

3. Theoretical analysis

3.1. Detection of the focal position and discontinuity and calculation of the focal length

To simplify our optical system, we simplify our setup to an optical schematic that includes a laser source with three propagating beams, two lenses with the same focal length, an OL placed at twice the distance between the OL and the specimen ($2u$) in Fig. 1, and a CCD camera. Because the cluster of laser beams passes through the OL, is reflected from the specimen, and passes through the OL again, this process could be treated as that the beam cluster passes through two lenses that are separated by two times the distance between the OL and the specimen in the original setup. Points D, I_1, I_2, and I_3 in the original setup (Fig. 1) are also shown in the analogous schematics (Figs. 2–5). Accordingly, point D is the origin of the beam cluster, which indicates

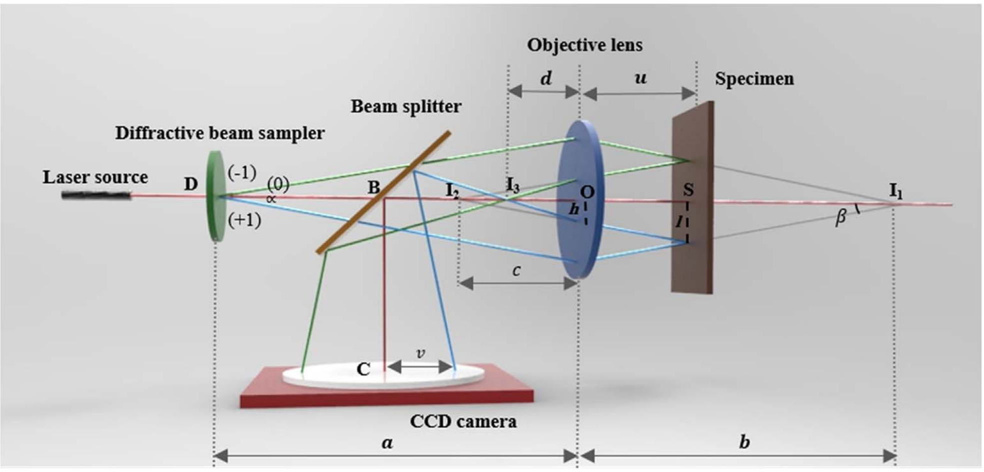

Fig. 1. Optical setup for the measurement of the focal length. In this setup, the DBS–OL distance is a, the distance between I_1 and the OL is b, the distance between I_2 and the OL is c, the distance between I_3 and the OL is d, the sum of the OL–BS distance and BS–CCD distance is ρ, and the distance between the OL and the specimen is u. The laser-beam-spot distance on the CCD camera is v, and the beam-spot distance on the OL is h.

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