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Real-time detection of focal position of workpiece surface during laser processing using diffractive beam samplers

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ABSTRACT

The real-time fabrication of microgrooves on a curved surface using a laser beam, without pre-programming their shapes into the machining instructions, is a major challenge in laser processing owing to limitations associated with the real-time detection of the focal position. A new approach using a sampled fraction of the beam from a diffractive beam sampler (DBS) is therefore presented in order to overcome this limitation. By considering the sampled fraction of the beam an analysis of the results allows for precise positioning of the specimen for focal-point identification. This allows for the determination of the focus for a broad variety of laser types and laser powers, thereby providing stringent focusing conditions with high numerical apertures. This approach is easy to implement, inexpensive, independent of the roughness or granularity of the workpieces, and more importantly does not require auxiliary lasers and displacement sensors for real-time measurement during the fabrication process.

1. Introduction

The increasing global enthusiasm surrounding laser micromachining and its commercial benefits has encouraged laser scientists to produce more flexible, effective, and versatile laser systems. The utilization of laser pulses has proved to be a fantastic approach in the qualitative micromachining of many materials and ability to wipe out or vary material characteristics and can be widely applicable [1–5].

The primary issue during laser processing (both in research and industrial applications) concerns focusing a laser beam onto a workpiece. A few schemes currently exist in the field of laser processing that can be used to detect the focal position. A common approach involves the observation of the beam diameters in a *z*-axis experiment [6–10]. This conventional approach is not always feasible because (i) the laser source may not be sufficiently powerful to induce the required modifications/ablation, and (ii) unacceptable permanent alteration/damage is induced on the target. A wide variety of autofocus systems are based on the following mechanisms: maximizing the reflected light signal detected behind a pinhole [11], viewing/imaging the specimen in the same beam path as the laser [12–14], and optical triangulation by means of a position-sensitive device [15]. All of these approaches employ auxiliary lasers in addition to working lasers with comparatively low-numerical-aperture optics; furthermore, these procedures must be completed before the fabrication process. Therefore, the focusing conditions are relatively tolerant.

Ordinarily, the flat surface of the workpiece is the main object of laser micromachining. If a deformation that is larger than the working focal range of the laser appears along the axis of the laser beam, the focal point will deviate from the processing area. Moreover, the deformation due to thermal destruction actuated by the laser or pre-existing deformation may lead to a specific domain of the workpiece being rough, despite the fact that a holder or substrate is used to tighten the workpiece. At the same time, it becomes challenging to mechanically control workpieces that possess curved surfaces without preprogramming their morphology into the machining instructions. One method of avoiding such limitations is to skim the surface of the specimen precisely during mechanical control and to tune the focusing of the laser beam properly.

In industrial applications [16,17], a displacement measurement sensor system is used to achieve real-time measurements. Besides its high cost and complexity, the use of a sensor for receiving feedback from the desired beam has some limitations. The exact form of the reflection depends on the geometry of the surface. When a laser beam strikes a rough or granular surface, it is

Abbreviations: CCD, charge-coupled device; DBS, diffractive beam sampler

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reflected in all directions owing to the microscopic irregularities of the interface. Accordingly, the feedback results contain diffuse reflection. Another method uses abeam splitter and a charge-coupled device (CCD) camera to detect the focal position. However, a plasma may be created during fabrication owing to the high-power laser, which commonly causes reflection problems and damage to the sensor in the CCD camera; therefore, the feedback results will not be exact. On the basis of these issues, real-time measurements constitute a major challenge that requires new methods in order to be overcome.

In this paper, in order to cope with the problems and limitations presented above, we demonstrate a real-time, non-destructive, and low-cost focus-determination system using the analyzed results obtained from the sampled fraction of the beam incident upon the surface. The proposed method is not affected by the morphology of the working area and allows for a detailed characterization of the sampling beam, including its position and power, as well as the feedback of the sample surface to the CCD camera. This system is easily adjustable in order to fit the shape of each surface, allows for real-time focus determination for all types of lasers, is compatible with high-power lasers, and provides stringent focusing conditions with high numerical apertures.

2. Theoretical model for the response of the sampled fraction of the beam

2.1. Fundamental description of diffractive beam samplers

The key point of the design is the diffractive beam sampler (DBS), which is shown in Fig. 1. From a collimated incoming beam, outgoing beams exit from the DBS with a propagation angle that is determined during the fabrication of the DBS, and is based on the system requirements; the propagation angle is highly precise (2.07°) [18]. The beams' separation is manipulated for the far-field so that the beams become more well-defined as they continue to propagate after the DBS. Furthermore, the high-power beam is allowed to transmit along the optical axis as a main beam, but two side beams also emerge with a low energy compared with the main beam. These two sample beams are placed to the left and right of the main beam (with orders of −1 and +1) and are designated by the given propagation angle between them and the given sample power distribution required by the technical specifications. For a configuration with a sampling distribution of 1%, the occupied intensity will be ~97.5% for the main beam (0th order) and 1% for the +1st and −1st orders [18]. The remaining power is distributed among the other (parasitic) orders. The propagation angle is twice as large as the sampled angle (α in Fig. 1).

2.2. Thin lenses and Gaussian beams

Consider a beam waist w_{01} as an object in which the wavefront has a radius of curvature $R_1(z)$ and a thin lens with a focal length f that is located at a distance d_1 away from it along the beam axis.

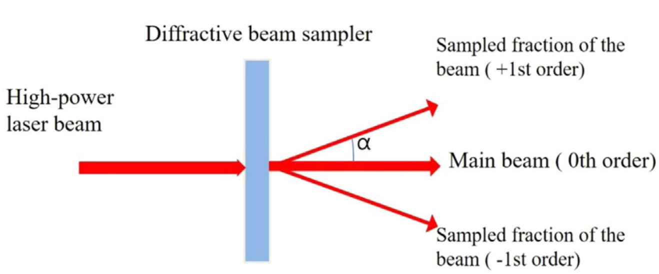

Fig. 1. Schematic diagram of a diffractive beam sampler (DBS).

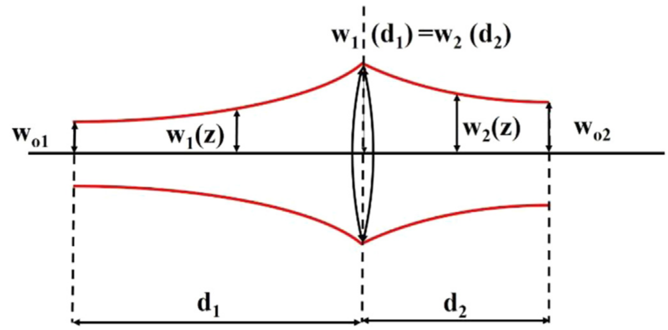

Fig. 2. Transmission of a Gaussian beam through a thin lens.

The image obtained is located at a distance d_2 away from the lens with a beam waist w_{o2} and a radius of curvature $R_2(z)$ (as described in Fig. 2). Furthermore, according to the definitions of the beam width and the radius of curvature of the wavefronts comprising the beam [19], the beam width can be expressed as follows:

$$w(z)=w_0\sqrt{1+\left(\frac{z}{z_R}\right)^2}, \tag{1}$$

where $w(z)$ is either $w_1(z)$ or $w_2(z)w_o$ is either w_{o1} or w_{o2} and $z_R=\frac{\pi w_0^2}{\lambda}$ is the Rayleigh range. The radius of curvature of the wavefronts comprising the beam is

$$R(z)=z\left(1+\left(\frac{z_R}{z}\right)^2\right). \tag{2}$$

By applying Eq. (2) and the formulation of a thin lens for a Gaussian beam, we have the following:

$$\frac{1}{R_1(d_1)}+\frac{1}{R_2(d_2)}=\frac{1}{f}\rightarrow\frac{1}{d_1\left(1+\left(\frac{\pi w_{01}^2}{\lambda d_1}\right)^2\right)}+\frac{1}{d_2\left(1+\left(\frac{\pi w_{02}^2}{\lambda d_2}\right)^2\right)}=\frac{1}{f}. \tag{3}$$

Furthermore, the beam widths at the lens must be equal for both the incident and outgoing beams—the beam widths are continuous at the lens position. By applying Eq. (1), we have

$$w_1(d_1)=w_2(d_2)\rightarrow w_{01}^2+\left(\frac{\lambda d_1}{\pi w_{01}}\right)^2=w_{02}^2+\left(\frac{\lambda d_2}{\pi w_{02}}\right)^2. \tag{4}$$

From Eqs. (3) and (4), we can obtain

$$\frac{d_2}{f}=1+\frac{\frac{d_1}{f}-1}{\left(\frac{d_1}{f}-1\right)^2+\left(\frac{\pi w_{01}^2}{\lambda f}\right)^2}. \tag{5}$$

Eq. (5) gives us the position of the beam waist of the outgoing beam as well as the position of the image of an arbitrary beam source with respect to the lens. In other words, if a cluster of beams starting at a distance d_1 away from the lens passes through the lens, they will converge at a distance d_2 on the other side of the lens.

2.3. Application to our experimental setup

The setup of this system for an out-of-focus reflecting surface is shown in Fig. 3, where a is the distance between the DBS and the objective lens, and u is the distance between the objective lens and the specimen. The laser beam originates from a laser beam source and is diffracted at the beam sampler. The beam sampler becomes a secondary laser source for three beams: (−1), (0), and (+1). In this section, we will consider the optical path of beam (+1). The beam originating from the beam sampler reaches the objective