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Excimer laser micromachining of aspheric microlenses with precise surface profile control and optimal focusing capability

Yung-Chun Lee[a,*,1], Chun-Ying Wu[b]

[a]Department of Mechanical Engineering, National Cheng Kung University, Tainan 701, Taiwan
[b]Institute of Micro-Electro-Mechanical-System, National Cheng Kung University, Tainan 701, Taiwan

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Abstract

This paper demonstrates the unique and exceptional capability of excimer laser micromachining in fabricating aspheric microlenses with precise surface profile control. A newly developed laser scanning method is introduced for machining refractive types of microlenses, which have pre-designed surface profiles aiming at minimizing the optical focal spot sizes. The machining accuracy and machined surface roughness are examined experimentally, and very good results are obtained. Optical testing on the fabricated aspheric microlenses shows significant improvement in focusing capability and the focal spot sizes are approaching optical diffraction limits. The proposed excimer laser micromachining method is flexible, versatile, and accurate, hence can be very useful and powerful in machining 3D microstructures of complex profiles and demanding profile accuracy.

Keywords: Aspheric lens; Microlens; Excimer laser; Micromachining

1. Introduction

Excimer laser micromachining technology is well known as a powerful tool for fabricating 3D microstructures [1–4]. It utilizes pulsed lasers of short wavelength such as ArF (193 nm), KrF (248 nm), XeCl (308 nm), and XeF (351 nm). The laser pulses usually have high pulse energy and short pulse duration, around a few to a few tens of nano-seconds. Upon projecting onto sample, the laser pulses interact rapidly with the sample material and result in material ablation from sample surface. The ablation mechanism is quite complicated and involves both photo-thermal and photo-chemical interactions [1,5]. In addition to the laser source, a typical excimer laser micromachining system usually equipped with an optical project system, which modulates the laser beam pattern with a photo-mask and then projects the pattern onto sample surface, and a servo-controlled mechanical scanning stage, which synchronizes the sample motion with the laser pulse firing. These additional capabilities allow an excimer laser micromachining system to carry out 3D microstructure microfabrication with great flexibility and machining accuracy.

In a recent paper [6], the authors have successfully developed a new mask contour scanning method for fabricating 3D microstructures with analog surface profiles using an excimer laser micromachining system. This method, named the "planetary scanning method", combines a self-spinning of the photo-mask and an orbital revolution of the mask around the sample. It has been shown in Ref. [6] that this method can fabricate axially symmetric 3D structures of an arbitrarily given surface profile with great profile accuracy. Both concave and convex microstructures can be fabricated with this method. In this work, the same method will be applied to fabricate aspheric microlenses with pre-designed surface profiles, which are meant to minimize the optical focal spot sizes. The goal is to evaluate the machined surface profile accuracy and surface roughness, and the optical performance in terms of focusing capability of these laser-machined aspheric microlenses. For the purpose of

*Corresponding author. Tel.: +886 6 2757575x62177; fax: +886 6 2352973.
E-mail address: yunglee@mail.ncku.edu.tw (Y.-C. Lee).
[1]Present address: Department Mechanical Engineering, National Cheng Kung University, Tainan 701, Taiwan.

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comparison, both spherical and aspheric microlenses are fabricated, and their optical performance have been experimentally determined and compared.

2. Excimer laser micromachining and planetary scanning method

For completeness, this section will briefly review and highlight the important elements of an excimer laser micromachining system and the planetary scanning method for fabricating refractive-type microlenses of given surface profiles. Fig. 1 schematically shows the excimer laser micromachining system (PS-2000, Excitech Ltd., Oxford, UK) used in this work. The system has a 248 nm KrF excimer laser (COMPEX 110, Lamda Physics, Germany) with a pulse duration of 30 ns (FWHM) and maximum 350 mJ/pulse. The system uses a pair of cylindrical lenses (LC1 and LC2) and a homogenizer to form a laser beam of uniformly distributed laser intensity profile. The laser beam then passes through a photo-mask and is projected by a 10 × demagnifing projection lens system onto the sample surface. The sample is placed on a PC-controlled motorized stage, which can travel in all three directions (x–y–z) and rotate (r) with respect to its center. The computer can trigger the output of laser pulses and synchronize the motions and rotation of the sample stage using an installed software program. A CCD camera is attached for monitoring the machining process as well as for sample alignment if needed. A beam profile viewer is included in the system for monitoring the homogeneity of intensity profile of the laser beam.

Excimer laser micromachining is basically two-dimensional and binary, which means that each single laser pulse removes a certain amount of sample material from the surface. The machining rate depends on laser fluence and sample's material properties. The machined pattern on the sample is a duplicate of the photo-mask's window-opening pattern with a downscaling factor of the demagnifing projection lens, which is 10 × for the PS-2000 system used in this work. For 3D micromachining, either the mask or the sample has to be in motion while the laser pulses are continuously firing. Superposition of the 2D machined patterns yields a machining depth variation and therefore results in a 3D micromachining on the sample surface [7–11].

For fabricating axially symmetrical 3D microstructures, a novel mask contour scanning method, the planetary scanning method, was proposed by the authors [6]. Fig. 2 illustrates the basic ideas. First of all, a photo-mask with a typical window-opening pattern as shown in Fig. 2(a) is prepared. The mask is made from a chromium-coated fused quartz blank by the standard photolithography method. The total arc length of the opening window at radius ρ is denoted by $S(\rho)$. ρ_o is the outer radius of the mask. If the mask is continuously rotating with respect to its center when the laser pulses are randomly triggered and projected on the sample, a probability distribution of laser machining on the sample surface is formed as

$$P_m(\rho) = \frac{S(\rho)}{2\pi\rho}, \tag{1}$$

where $P_m(\rho)$ is called the mask probability function and is represented by the gray scale level in Fig. 2(b). It should be mentioned that the concept of mask probability function is based on the following: (a) the laser machining rate (μm/pulse) is small, hence (b) the total number of laser shots is large, and (c) the laser triggering is randomly but evenly distributed over the rotation of mask. Therefore, the distribution of total numbers of laser shots projected on the sample surface can be related to the mask probability function, which is axially symmetrical, as shown in Fig. 2(b). For a planetary scanning laser machining, as shown in Fig. 2(c), the mask is first offset by a distance r_o from an original point of the sample (point O) and then keeps scanning around an orbit centered at point O with a radius of r_o while maintaining its rotation with respect to its own mask center. In real applications, the sample stage is performing the self-rotation and orbital revolution

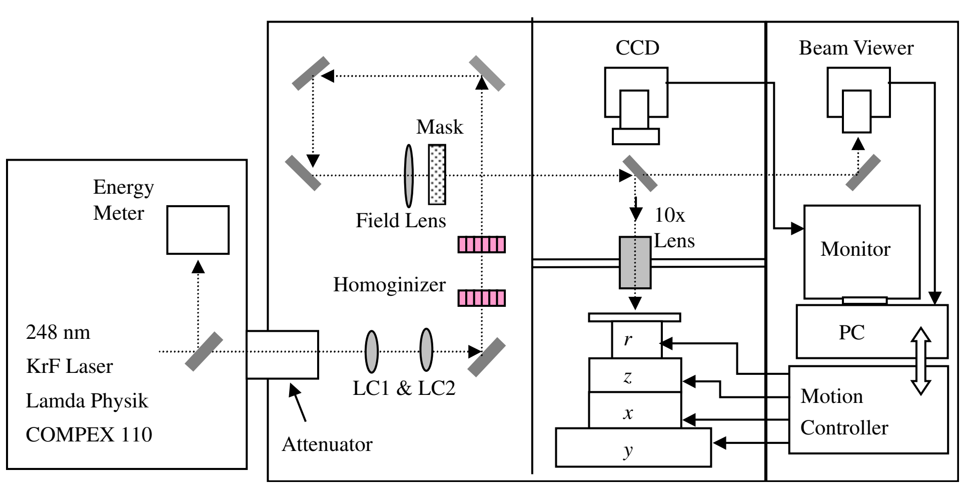

Fig. 1. Schematic diagram of PS-2000 excimer laser micromachining system (Excitech Inc., Oxford, UK).