Analogous Micro-optical Components Fabricated Using Excimer Laser Ablation

Hsiharng Yang\textsuperscript{1} and Cheng-Tang Pan\textsuperscript{2}

\textsuperscript{1} Institute of Precision Engineering
National Chung Hsing University
Taichung, Taiwan 402, R.O.C.
\textsuperscript{2} Mechanical Industry Research Laboratories
Industrial Technology Research Institute
Hsinchu, Taiwan 310, R.O.C.
Email: hsiharng@nchu.edu.tw

Abstract

The numerical simulations were used to predict the profile of analogous microstructures following excimer laser ablation to obtain desired micro-optical components. The simulation technique applied in the excimer laser ablation can reduce the quantity of machining experiments. The ablated microstructures with surface roughness of $Ra < 20$ nm were successfully machined into micro-optical components for further applications. The excimer laser machining parameters included laser energy, shot number, and repetition rate. 3-D microstructures formations were numerically simulated. Various micro-optical components with low aspect ratios can utilize these laser ablation numerical simulations and to form desired application geometries.

Key Words: Microlens, Excimer Laser, Micromachining, MEMS

1. Introduction

Micromachining technology has a wide range of applications, optical-electro mechanisms are particularly attractive. Micro-optical functions and devices, such as focal plane optical concentration, optical efficiency enhancements, color separation, beam shaping, and miniature optical scanning, have shown potential in the industry [1]. The development of micromanufacturing technology has allowed compact and mini-features to be fabricated. Micro-electro-mechanical system (MEMS) technology offers a wide variety of applications for the military, industrial, and consumer markets [2]. Numerous academic and research institutions have been involved in the development of MEMS technology and commercial products [3]. The miniaturization of components has been a common objective in all studies. Miniaturizing devices using micro-optics promises to revolutionize many electro-optical systems – from video cameras, video phones, compact disk data storage to robotics vision, optical scanners and high-definition projection displays [4,5]. Both higher accuracy and lower cost microlens fabrication methods are needed to meet the rapid demand for these commercial devices.

Multi-mask-level photoresist patterning and sequential reactive-ion etching (RIE) to form binary optic microlens arrays has been achieved was realized [6]. A laser writing system for the fabrication of continuous-relief micro-optical elements in photoresist was described by Gale et al [7]. Polymeric materials are quite suitable for microstructuring due to their low ablation threshold, smooth etching behavior, and ablation rates at tenths of micrometers per pulse at very
modest energy fluence [8,9]. Zimmer et al. developed efficient methods to fabricate analogous three-dimensional (3-D) structures with dimensions in the micron range [10]. Deep X-ray lithography processes, electroforming and molding technology (also as known LIGA process) to fabricate micro-optical components shows great potential for mass production [11].

Micro-optical components of any desired shape with smooth surfaces, lateral dimensions in the micrometer range, and heights up to several hundred micrometers can be achievable via excimer ablation [12]. Following a molding process (hot embossing), analogous micro-optical components in polymer can be attained for mass production. Thus, the design, simulation, and fabrication process of micro-optical components can be implemented through theoretical study and experiments.

2. Experimental

The Exitech 8000 type excimer laser workstation was used in these experiments and is schematically described in Figure 1. The laser source was a Lambda Physik COMPEX-110 excimer laser whose wavelength, pulse energy, pulse time, and peak pulse repetition rate are 248 nm, 400 mJ, 25 ns, and 100 Hz respectively. The laser beam focused spot size used in this study was $0.25 \times 0.25 \, \text{cm}^2$. A constant discharge voltage mode and constant pulse energy mode are available during micromachining. The photomask projection method was applied for micromachining after a constant voltage or pulse energy mode was setup. A set of twin array energy density homogenizers and a projection lens were installed to make the laser beam power profile more uniform. The working parameters of the laser machine were pulse number, energy density, and pulse repetition rate, ranging from 30-80, 0.152-0.642 J/cm², and 1-80 Hz respectively. The laser ablated polymer microstructure surface measurement was scanned using AFM (atomic force microscope) and SEM micrograph to show the 3-D morphology. The ablated depth was measured using a Dektak II surface profiler (ablated depth $\leq 30 \, \mu\text{m}$) and OM (optical microscope).

3. Working Principle

The working parameters of excimer laser included laser energy, shot number, scanning velocity and pulse repetition rate. The relationship between these parameters can be expressed as

$$f = \frac{s \, H}{V} \quad (1)$$

where $f$: laser frequency
S: laser shot number
H: height of mask pattern in scanning direction
V: scanning velocity

From the above equation, it can be seen that through there are three laser machine variables, i.e., $V$, $S$, and $f$, only two of them are independent. Eq. (1) can be rearranged as

$$H = \frac{SV}{f} \quad (2)$$

Eq. (2) reveals that $H$ is proportional to $S$. When a larger $H$ is exposed to the laser beam energy, deeper workpiece ablation thickness will be the result. Based on the above mentioned facts, different mask patterns can be designed to obtain patterns with various $H$ dimensions. The laser energy profile in the mask pattern in terms of the laser shot number (Eq. 2) can be calculated, with which the 3-D microstructure can be analogously predicted.

$$D \propto S \quad (3)$$

where $D$: ablation depth.

However, the substrate thermal and photochemical properties were not yet taken into consideration. This will play an important role in laser ablation. Thus, depth is a function of $S$ and $K$. $K$ can be treated as a calibration number. It is a function of the material thermal and photochemical properties. The relationship can be expressed as follows:
\[ D \propto KS \quad (4) \]

where K: thermal and photochemical properties.

Based on Eqs. (2) and (3), as long as the mask pattern is defined, the 3-D microstructure produced using laser ablation can be predicted.

To enhance the surface smoothness, a thermal reflow process is then properly applied. The procedure is described in Figure 2.

### 4. Results and Discussion

This experiment is based on the laser pulse number, energy density, and pulse repetition rate to investigate their correlations to the laser machining results. Ablation depth versus laser shot number is discussed below. Figure 3 shows the ablation depth versus the laser shot number. It makes sense that a higher laser shot number results in a higher ablation depth at a constant repetition rate. It is worth noting that the relationship between ablation depth and shot number shows an excellent linearity. Figure 3 verifies experimentally with Eq. (2).

The profile of analogous 3-D micro-optical components can be simulated using numerical analysis using Eqs. (2) to (4). The simulation result is illustrated in Figure 4. Experimental and predicted ablated patterns are compared. Experimental results show a good agreement with the simulation profile qualitatively. A spherical lens is shown with 3-D and top views.

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**Figure 2.** Schematic drawing of the laser ablation fabrication process

- (a) Polymer on Etching Stop Layer
- (b) Laser Dragging Micromachining
- (c) After Cross Micromachining
- (d) Reflow Diffusion/RTA/High Energy Beam
- (e) Sputter (Seed Layer)
- (f) Electroforming (Ni-Alloy)
- (g) Stripping

**Figure 3.** The experimental result of excimer laser ablation

**Figure 4.** Simulation result of excimer laser ablation
This simulation method also can be applied to a spherical lenses array. The preliminary result is shown in Figure 5(a). An incomplete spherical lenses array is illustrated in Figure 5(b). The ablation depth was not deep enough to form the desired depth due to an insufficient number of shots. The proper laser energy and shot number can improve the geometric shape and surface roughness (shown in Figure 5(c)).

Complex geometric structures can be simulated and patterned using laser dragging. A micro-prism array can be also predicted using this method. Figure 6(a) displays the simulation result. A micro-prism array (Figure 6(b)) cannot be machined using the conventional lithography process, but they can be easily ablated using an excimer laser. Various shapes and size can be controlled using different laser ablation machining parameters. The sharpness of these prisms are very obvious (shown in Figures 6(b), (c)).
Analogous microstructures can be applied as micro-optical components in many fields. Surface smoothness in optical components is a required property. The laser ablated 3-D microstructures adapts to this requirement and the surface roughness of microstructures with Ra < 20 nm was measured using AFM (Figure 7).

Figure 6. The comparison between experimental and simulation prism results

Figure 7. Surface quality using an AFM after excimer laser machining

5. Conclusion

A micromachining process to fabricate analogous micro-optical components using excimer laser ablation was explored in this study. Various shapes and sizes can be controlled using different laser beam ablation machining parameters. Spherical lenses and micro-prism arrays were simulated. The surface quality of these eximer laser ablated components meet the critical requirements of micro-optical components. Experiments proved the feasibility of
excimer laser ablation on micromachining optical components at the micro-scale.

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**References**


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