Analysis and fabrication of minifeature lamp lens by excimer laser micromachining

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A variety of shapes of lamp lenses at the feature millimeter scale have been extensively used in lamp design. To further improve the light efficiency and to reduce the overall dimension of lamps, the lamp lens at the micrometer scale is fabricated by excimer laser cross scanning on a polycarbonate sheet. To verify the proposed method, the influence of an optical system with various shapes and sizes of lamp lenses on the light efficiency is explored in advance by ASAP optical software. The lens with a miniature feature can produce a smaller divergence angle than that with a large-size lens feature. The experiment is carried out at varying laser operating parameters, mask shape, and dimensions. The simulation shows that the desired lamp lens profile can be effectively produced by excimer laser micromachining. ©2007 Optical Society of America

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1. Introduction

Various lamps have been widely developed for automobile manufacturers in response to the demand for both attractive visual effects and small depth lamp production [1–3]. A large number of papers presenting various shapes of reflectors, such as parabola, circle, rectangle, and free-formed surface, have been presented [4–7]. A conventional lamp system is generally composed of an incandescent bulb, a reflector, and a transparent lens. The main function of the reflector in a lamp system is to reflect the beams from the bulb to form the uniform parallel beams, while the function of the lens is designed exclusively to diffuse the reflected beams from the reflector. Currently, the lamp lens at the feature millimeter scale is mostly machined by conventional mechanical machining methods such as turning, milling, and grinding [8–10]. Although the lamp lens can be produced precisely using these mechanical machining methods, they are not economic for producing repeating features in a large area.

The influence of various shapes of lamp lens on light efficiency has been explored [11,12]. The excimer lasers have been extensively applied to micro-machining of polymers since 1982 [13,14]. The excimer laser is suitable for ablating polymers because the dissociation energies of various chemical bonds for polymers are between 3.9 and 7 eV [15]. The miniature lamp lens produced by excimer laser machining is rarely studied. To prove the feasibility of miniature feature scale, including various shapes and sizes of the lamp lens, the miniature lamp lenses produced by the excimer laser cross scanning in different directions, taking into account the mask parameters, the laser operating parameters, and ablation characteristics of polycarbonate (PC) material, are designed and fabricated.

2. Miniature Patternning

A. Optical Advantages of Miniaturization

The ASAP optical software (registration 24349 204y0m4d 0n2i2v64 3b4g0s3v 6e2f6744) has been de-
developed for many years to assist the optical design of lamps. To prove the feasibility of miniature lenses used for the lamp, we explore several optical systems with various shapes and sizes of lamp lens. Each of these optical systems is composed of three parts, such as a light source, a lens array, and an energy detector. The spherical and pillow lamp lenses are most often utilized in the lamp at present. First, optical systems with spherical shapes of lamp lenses and various sizes of lamp lenses are analyzed. Figure 1 shows a spherical lamp lens with a unit size of $5 \times 5$ mm and a radius of curvature of $4.8$ mm; Fig. 2 shows a spherical lamp lens with a unit size of $0.1 \times 0.1$ mm and a radius of curvature of $0.48$ mm. Figure 3 shows a pillow lamp lens with a unit size of $4 \times 6$ mm and a radius of curvature of $6.5$ mm; Figure 4 shows a pillow lamp lens with a unit size of $0.1 \times 0.15$ mm and a radius of curvature of $0.65$ mm. From the optical simulation, one knows the optical systems with miniature lamp lenses can produce a smaller divergence angle and larger illuminance as well as more uniform luminous intensity distribution on the illuminated region than those with large-size lamp lenses. The minifeature lens offers a much smaller divergence angle than the macrofeature lens as listed in Table 1.

B. Processes of Lens Fabrication
A flow chart of the lens fabrication process is shown in Fig. 5. The optimal lens manufacturing process depends on the constructed model, shape, and size of the mask, laser operating parameters, and fabrication method. The sequence can be divided into simulation of the profile and a machining experiment. If the deviation between computer simulation and machining experiment is higher than 10%, the process has to go back to the modification of the model for further process design.

C. Mask Design
There are several kinds of shapes and sizes of lamp lenses used in the lamp design. Among these shapes of lamp lens, spherical and pillow lamp lenses are most often utilized. The two shapes of lamp lenses are fabricated by excimer laser cross scanning in the investigation. To produce the desired three-
dimensional micropatterning, design of the mask and control of the laser operating parameters have to be taken into consideration in advance.

3. Laser Scanning Principle

To produce the desired minifeature lamp lens, the half-circular shape of mask with various sizes is used in this paper. The laser scanning technique to produce the lens can be divided into three categories, namely, both the mask and the workpiece are stationary; either the mask or the workpiece is movable, and both the mask and the workpiece move synchronously while the laser is firing. The desired three-dimensional lamp lens can be manufactured by the laser cross-scanning method with appropriate mask design, precise motion of the stage, and control of the laser operating parameters. The schematic is illustrated in Fig. 6. The lens profile is determined by the shape of the mask because the ablation depth of the groove is proportional to the height of the mask pattern during the scanning process. Figure 7(a) shows that height \( H \) of the mask pattern is a function of \( x \), and Fig. 7(b) shows that ablation depth \( D \) of the profile increases when the scanning velocity decreases in the \( Y \) direction. To produce the desired lens profile, a model predicting the ablation depth of PC material by the KrF excimer laser scanning with a half-circular shape of the mask is applied [16]. The proposed model is expressed as follows:

\[
D = \frac{1}{\beta} \ln \left( \frac{(1 - R)E}{F_{th}} \right) \frac{fH A_f f_s}{V A_o} \frac{d_{drag}}{d_{fixed}}
\]  

where \( \beta \) is the absorption coefficient of PC material; \( R \) is the reflectivity; \( F \) is the fluence (mJ/cm²); \( F_{th} \) is the threshold fluence (mJ/cm²); \( f \) is the pulse repetition rate (Hz); \( H(x) \) is the height of the mask pattern of a function of \( x \) (\( \mu \)m); \( V \) is the scanning velocity (mm/min); \( A_o \) is the original area of the mask for

<table>
<thead>
<tr>
<th>Lens Feature (mm²)</th>
<th>Divergence Angle (deg)</th>
<th>Maximum Illuminance (1×)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 × 5</td>
<td>25</td>
<td>0.009</td>
</tr>
<tr>
<td>[(50 × 0.1) × (50 × 0.1)]&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8.12</td>
<td>0.077</td>
</tr>
<tr>
<td>4 × 6</td>
<td>28.7</td>
<td>0.018</td>
</tr>
<tr>
<td>[(40 × 0.1) × (40 × 0.15)]&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6.06</td>
<td>0.146</td>
</tr>
</tbody>
</table>

<sup>a</sup>The 50 × 50 lens array with the lens size each of 0.1 mm × 0.1 mm.

<sup>b</sup>The 40 × 40 lens array with the lens size each of 0.1 mm × 0.15 mm.
laser scanning machining; \( A_f \) is the final area of the mask for laser scanning machining, \( f_s \) is the frequency of 20, 40, 60, 80 Hz; \( d_{\text{drag}} \) is the ablation depth by laser scanning process; and \( d_{\text{fixed}} \) is the ablation depth by machining at fixed position.

4. **Experimental Setup**

A KrF excimer laser is used for the experiments. Its wavelength, maximum pulse energy, pulse duration time, and maximum repetition rate are 248 nm, 350 mJ, 25 ns, and 100 Hz, respectively. The laser beam is shaped and homogenized by a 6 \( \times \) 6 fixed-array homogenizer to illuminate the mask plane. The mask pattern is projected onto the workpiece by a projection lens with 4\( \times \) demagnification factor. To guarantee high machining quality, the Z axis must be readjusted according to the thickness of each workpiece. During operation, all the experiments are conducted in a clean room of class 1000. We used a 1 mm thick PC sheet made by Goodfellow because it is widely used for automotive lenses. The shape of the miniature lamp lens is measured by a three-dimensional confocal surface measurement system and a WYKO optical profiler. The three-dimensional images of the machined profile were taken by a scanning electron microscope (SEM).

5. **Results and Discussion**

Figures 8 and 9, respectively, show the results of both experimental and numerical simulations from laser cross scanning with the half-circular shape of the mask and various mask sizes. The experimental and predicted depths of the cross profile in Fig. 8 are 6 and 6.32 \( \mu \text{m} \), respectively, and the experimental and predicted depths of the cross profile in Fig. 9 are 6.9 and 7.26 \( \mu \text{m} \), respectively.
To produce a spherical lens with a radius of curvature of 0.48 mm as shown in Fig. 8, the same mask parameters are used for laser cross scanning in both directions. However, to produce a pillow lens with a radius of curvature 0.65 mm as shown in Fig. 9, various mask parameters have to be used for laser cross scanning in the X and Y directions. Figure 8 shows the lens feature of a spherical shape produced by laser cross scanning with the same operating parameters in two directions; Fig. 9 shows the lens feature of a pillow shape produced by laser cross scanning with various operating parameters in two directions.

Spherical and pillow shapes of lamp lenses with the microsize feature fabricated by the laser cross scanning with various shapes of masks are designed based on the model of Eq. (1). The desired profile of the lamp lens can be effectively predicted based on the model of ablation depth. These experimental results show good agreement with the prediction. The deviation between both experiment and simulation is under 10%. The difference is attributed to the defocus effect that occurred on the workpiece surface during the second scanning.

6. Conclusion
An excimer laser cross-scanning process with a half-circular shape of the mask to fabricate miniature lamp lenses on a PC sheet has been presented. A variety of shapes and sizes of lamp lenses can be fabricated by varying laser operating parameters, shape of the mask, and mask parameters. The desired profile of a lamp lens can be effectively predicted based on the model of ablation depth. The experimental results show not only good agreement with the predicted profile but also prove the feasibility of making the lamp lens with miniature feature and higher lamp efficiency.

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References