Replication of a large size Fresnel type concentration lens for photovoltaic solar cell using spin coating

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Abstract
In this study, we applied spin coating method to replicate a large size solar concentration lens. Although power generation from photovoltaic solar cell is a clean energy resource from the nature, its applications are limited due to its high cost and low efficiency. To challenge these difficulties, concentrated photovoltaic (CPV) solar cell attracts attention. The solar concentration lens is usually made of plastic materials and replicated by hot embossing and injection molding methods. However, plastic lenses have weak durability for heat and UV. Therefore, silicone based lenses are presented. Moreover, the spin coating method can replicate a large size micro-patterned lens from silicone material at room temperature and atmospheric pressure. In particular, Fresnel type of lens design is suitable for spin coating due to its thin and uniform thickness. The diameter of the lens is 160 mm to achieve X1000 of concentration ratio. The diameter and optical power of focused beam are measured along the distance, and the generated power is also compared between non-concentrated and CPV solar cell.

1. Design

1.1 Aspherical lens design
Refractive type of CPV requires Fresnel lenses to focus sun rays on solar cells. The focal length was selected to be 1 m to avoid an overlap considering array installment. The diameter of the lens was set at 160 mm to achieve X1000 ratio considering the size (5 mm) of the solar cell. Aspherical lens design provides a more effective way to achieve high optical efficiency.
Table 1. Optimized parameters of aspherical lens

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R/mm</td>
<td>430.7058</td>
<td>B/mm^3</td>
<td>-4.0748e-16</td>
</tr>
<tr>
<td>k/1</td>
<td>0</td>
<td>C/mm^3</td>
<td>3.0635e-20</td>
</tr>
<tr>
<td>A/mm^3</td>
<td>3.2028e-9</td>
<td>D/mm^3</td>
<td>-1.2022e-26</td>
</tr>
</tbody>
</table>

Table 1 shows the optimized coefficient for aspherical equation \( z(r) \). Sun rays are assumed as three dominant wavelengths as 486.1 nm, 587.6 nm and 656.3 nm.

1.2 Fresnel lens design

An aspherical lens could be transformed into a Fresnel type by dividing it into a prism pattern. If Fresnel edge is divided at a constant period, cutting depth will be deeper at the center compared to the outer side. This may cause not only serious errors in geometry, but also a rough surface due to tool wear. Therefore, lens mold was machined using an ultraprecision turning machine (AHN15, JTekt Co.) by limiting the maximum depth to be under 20 \( \mu m \).

2. Fabrication

2.1 Replication process

The Fresnel type aspherical lens has an almost flat surface, and for such reason it could be beneficial to use the spin coating method. Material of the lens was liquid polydimethylsiloxane (PDMS), which is composed of Sylgard 184A and a curing agent with 10:1 weight ratio. Defoamed PDMS was poured on the lens mold and flattened using spin coating [2]. Figure 1 shows the spin coating of the PDMS and a detaching process of the cured lens. Liquid PDMS requires 48 hours to be cured at ambient temperature and thermal energy accelerates the curing time. The coated lens mold was cured in an oven at 80 °C for two hours. Replicated thin film lens has the same optical properties as a solid lens.
2.2 Spin coating condition

Spin coating method utilizes the equilibrium between viscous force and centrifugal force. Therefore, rotation speed and time are design parameters. N. Sahu et al [1] presented an equation for average thickness \( h_t \) with rotation speed and time.

\[
h_t = h_0 / \left(1 + 4h_0^2kt\right)^{0.5}, \quad k = \frac{\rho \omega^2}{3\eta}
\]

with initial thickness \( h_0 \), time \( t \), fluid density \( \rho \), absolute viscosity \( \eta \) and angular rotational speed \( \omega \).

<table>
<thead>
<tr>
<th>Rotation speed/RPM</th>
<th>100</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average thickness/( \mu \text{m} )</td>
<td>400</td>
<td>280</td>
</tr>
<tr>
<td>Deviation/( \mu \text{m} )</td>
<td>( \pm 75 )</td>
<td>( \pm 2 )</td>
</tr>
</tbody>
</table>

Figure 2. Estimation of lens thickness

Figure 2 represents the estimated average thickness of a replica according to rotation speed and time. In the real experiment, rotation time was selected as 30 seconds. Although high rotation speed results in thin thickness, table 2 shows the improved thickness deviation along the radial direction.

3. Experiment

3.1 Edge replication

All Fresnel edges are components of an aspherical surface. Fresnel type lens has ideally the same optical properties as a solid one. However, an imperfect Fresnel edge provides defects on the lens surface and deteriorates the optical efficiency. Therefore, an inspection of edge shape is required. A white light interferometer provides the surface profile which shows the edge shape of lens mold and replica. Figure 3 compares the Fresnel edges. The profile for the replicated edge was reversed from the profile of the mold. The edge height was 5 \( \mu \text{m} \) and geometrical error was 0.02 \( \mu \text{m} \).
3.2 Optical characteristics

Replicated CPV lens was installed under natural sun light. The intensity of sun light changes depending on the weather, cloudness and region. Therefore, reference intensity was measured by an optical power meter during the experiment. Table 3 shows that a replicated concentration lens improved the photovoltaic power. However, it could not reach the optical magnification ratio due to the low conversion efficiency resulting from the temperature rises.

Table 3. Comparison of photovoltaic power

<table>
<thead>
<tr>
<th>Reference intensity/(W/m²)</th>
<th>Photovoltaic power/mW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Direct</td>
</tr>
<tr>
<td>450</td>
<td>1.37</td>
</tr>
<tr>
<td>560</td>
<td>3.61</td>
</tr>
<tr>
<td>700</td>
<td>4.83</td>
</tr>
</tbody>
</table>

4. Conclusion

Spin coating of liquid silicone can replicate a large scale of micro patterns. Especially, a Fresnel type CPV lens provides a high concentration ratio with a thin film replica. Concentration experiments were conducted under natural sunlight and increment of photovoltaic power was observed.

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References: