Research on the Relationship Between the Performance and Geometry of Secondary Optical Elements in Fresnel Concentrating System

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Abstract: Secondary optical elements play an important role in solar concentrating systems, including increasing tracking error tolerance and radiation flux homogenization. In this paper, for the Fresnel lens concentrating system, the SOEs with various geometric shapes are compared, including the quadrangular frustum pyramid SOE(KFTS-type SOE), quadrangular prism SOE, circular frustum SOE, cylinder SOE and concave lens. The influence of the shape of the incident plane and the length of the SOE on the uniformity of the solar radiation distribution of the output spot is analyzed by Monte Carlo rays tracing method. Simulation results show that KFTS-type SOE has advantages in improving the radiation uniformity of the receiving surface. Furthermore, two new SOEs are designed on the basis of KFTS-type SOE, one of them has a significant improvement in increasing the acceptance angle when using the same amount of materials.

1. Introduction
Since the 1970s, with the advancement of industrialization, energy and air pollution problems have become increasingly serious, people have focused on renewable resources. Solar energy has the advantages of sustainable, pollution-free and low-cost, so it has become a major energy development direction. Photovoltaic cell is a main way to utilize solar energy. Generally, Fresnel lens is used as primary optical element (POE) in Fresnel concentrating systems to focus sunlight on a small area to improve optical efficiency, but at the same time, it will lead to uneven the solar radiation distribution, therefore increase of temperature of solar cells and decrease of efficiency. Therefore, it is necessary to control the concentration rate and use a homogenizer to make the light evenly distributed. Secondary optical elements (SOE) have the advantages of simple fabrication and strong uniformity. We use Monte Carlo ray tracing algorithm to judge the uniformity of spot energy flow by tracing a large number of rays. $I_a/I_{max}$ is the irradiance normalized to the maximum irradiance, and the uniformity is defined as $(1-(1-I_{amin})/(1+I_{amin}))$.

Ordinary POE uses PMMA plastic Fresnel lens, but the general Fresnel lens will form concentric circular spot with large middle irradiance and small peripheral irradiance on the square solar cell. For this reason, specific concentrating systems are developed to avoid the problem[1-3]. The efficiency of general silicon solar cell or III - V compound solar energy cell will decrease with the increase of surface temperature, although the degrees of decline are different. Homogenizing the light can reduce the temperature of the overheated part in the middle of the battery, improve its efficiency, and make full use of the parts that are not illuminated at the four corners.
SOE is usually made of glass material, which is usually composed of sphere, prism and other basic geometries. We usually keep the focus of POE on the incident surface of SOE. The incident light is reflected or refracted several times in the SOE to form a uniform spot at the exit surface close to the solar cell. Different types of SOE have been designed for different specific situations[4-10], new-type Fresnel lenses are also developed [11]. The general solar cell is square, a typical quadrangular frustum shaped SOE(KFTS-type SOE) can well disperse the light, improve the uniformity, and the processing of this type of SOE is simple, so it is widely used. In this paper, the parameters of KFTS-type SOE are analyzed and compared, and some improvements are made at the same time. The optical efficiency is related to several parameters[12], including the distance between Fresnel lens and cell [13], the tracking error angle[14-15], optimization tracing systems are therefore developed[16-17].

Figure 1 shows the schematic diagram of Fresnel focusing system. The light is focused on the bottom of SOE through Fresnel lens, and then reflected or refracted by SOE to form spot on the solar cell.

2. Performance comparison between KFTS-type SOE and other SOEs

Table 1. Parameters of Fresnel concentrating system.

| Parameter                     | Value                  |
|-------------------------------|------------------------|
| Radius of Fresnel Lens        | 100mm                  |
| Prism pitch of Fresnel lens   | 0.3mm                  |
| Material of Fresnel lens       | Plastic(PMMA)          |
| Thickness of Fresnel lens      | 3mm                    |
| Focal length of Fresnel lens   | 150mm                  |
| Wavelength                    | 546.1mm                |
| Light source                  | Solar distribution     |
| Index of refraction of PMMA   | 1.4935                 |
| Material of SOE               | BK7                    |
| Index of refraction of BK7     | 1.51872                |
| Size of solar cell            | 4mm × 4mm              |

Table 1 shows the design parameters of the Fresnel lens and some parameters of SOE.

KFTS-type SOE is in the shape of a frustum. The bottom and top surfaces of KFTS-type SOE are two squares, one large and one small, and the four sides are isosceles trapezoid. Firstly, the SOEs of the first incident plane with different shapes and the same parameters are compared to determine whether the quadrangular frustum is the optimal geometric shape, SOEs with different shapes have been tested to determine the best geometric shape for SOE[18]. The SOEs under test in this paper are respectively frustum with circular bottom, frustum with star shaped bottom, four edge twisted frustum and ordinary frustum, as shown in the figure below, which are marked as A-type, B-type, C-type and O-type respectively. The bottom area is 8mm×8mm, the length is 20mm.
Figure 2 shows a stereogram of SOE with different bottom shapes. Figure 3 shows the irradiance distribution with four types of SOE respectively. It can be seen that the quadrangular frustum does have the best homogeneous effect, and it shows that the shape of the bottom of the frustum is closely related to the distribution of light. The frustums of star shaped and circular bottom are not uniform enough. The light reflected by the circular bottom frustum is concentrated in the center, and the light reflected by the star bottom frustum is concentrated in four corners. According to the irradiance distribution in different situations, it can be seen that there is a strong correspondence between the irradiance pattern and the bottom surface. From this point, it can be inferred that the effect of the frustum on the square bottom should be better. At the same time, the square is the neutralization of circle and star, and the radiation distribution of star and circle shows complementary relationship, which shows that it is very important to ensure that the outer layer of each cross-section of SOE is square to keep the uniformity of SOE. At the same time, the radiation pattern of the twisted frustum also shows obvious directivity, so it is necessary to ensure the axial symmetry of the prism. It is an important conclusion that every cross section must be of the same shape and not rotated.
Figure 3. Irradiance distribution of the receiving plane with different types of SOE.
At the same time, we can see that there is less illumination on the diagonals of the quadrangular frustum, which is caused by the secondary reflection of the light at the edge.

The length of SOE also has a considerable influence on the uniformity of the radiation pattern, because the length of SOE will determine the number of times the light from different angles is reflected in the SOE.

Figure 4. Irradiation uniformity-length curve of a quadrangular prism SOE with 4×4mm bottom

Figure 4 shows the effect of the length of SOE on the irradiance uniformity. As a whole, the uniformity increases with the increase of the length, and it also presents a rough periodic law. The reason is that the light rays incident at a certain angle travel in a circular symmetry. After passing through the period length L, they are reflected twice more, and the light spots formed on the exit surface are the same as the original ones; however, the cross sections of the light rays incident at different angles are different, and the period length L′ is different, that is, L is a function of the incident angle θ, and L(θ) is negatively related with θ, so the radiation patterns are approximate under the influence of a certain average period length L. In practical application, we can focus on the reduction of cost or the improvement of uniformity according to the actual requirements, and select the peak value of a certain period to achieve relatively uniform requirements.

Figure 5. Irradiation uniformity length curve of a quadrangular prism SOE with 4×4mm bottom and a KTFS-type SOE with with 8×8mm bottom and 4×4mm top
Figure 5 shows the irradiance uniformity with both KFTS-type SOE and quadrangular prism SOE. It can be seen that the variation trend of the uniformity of a frustum with its length is roughly the same as that of a prism (because a prism can also be regarded as a special frustum), but due to the existence of a certain inclination angle, it does not show periodicity like a prism. Generally speaking, the uniformity of the frustum is slightly better than that of the prism, and the curve is more stable. The uniformity of the frustum does not change much from 19mm in length. Because the frustum can significantly improve the acceptance angle, it is more widely used in the condition that the tracking system error is large.

In addition to square photovoltaic cells, there are also circular photovoltaic cells in common use. It is necessary to explore the performance of circular frustum SOE, cylinder SOE and concave lens. For circular frustum SOE, the radius of incident surface is 4×4mm and the radius of receiving surface is 2×2mm; for cylinder, the radius is 2mm.

Figure 6 shows the irradiance distribution of the receiving plane with cylinder SOE with different lengths. It can be seen that the accuracy of the length of the cylinder can be very high. If the difference is 1-2mm, the uniformity will be greatly different. Moreover, each longitudinal section of the cylinder is exactly the same rectangle in shape, which is not conducive to the dispersion of light. Therefore, unlike the square prism, there is a critical length. When the cylinder reaches the length that makes the radiation pattern most uniform, the uniformity will continue to decline. Figure 6d shows the irradiance pattern in the situation of a cylinder with a length of 50mm, which is already very low. This is an obvious disadvantage compared with the KTFS-type SOE and quadrangular prism SOE.

As a kind of refractive SOE, concave lens has a certain use space because of its advantages of simple processing and low cost. According to the size of the photovoltaic cell, the curvature radius of
the required lens can be calculated simply by the lens maker’s formula. However, SOE is usually placed near the Fresnel lens, and the spherical aberration has a great influence on it, which makes it impossible to form a highly approximate plane wave, resulting in low uniformity. However, we can make the outgoing light as close to the plane wave as possible, while reducing the accuracy requirements and improving the uniformity.

Figure 8. optical path of system with SOE concave lens

Figure 8 shows the approximate plane wave light forms a cylinder at a certain distance behind the exit surface.

Figure 9. irradiation distribution with concave lens as SOE (a) receiving surface is 7.5mm from the lens center; (b) receiving surface is 8.5mm from the lens center; (c) receiving surface is 9.5mm from the lens center.

Figure 9 shows the irradiation distribution with concave lens as SOE when the length between the receiving surface and the lens center changes. The variation of uniformity with distance is much smaller than that of cylinder and frustum, but there is still a gap with the former two in terms of the maximum uniformity, so it is suitable for the system with lower requirements for uniformity.

3. Optimization design of KFTS-type SOE

The front end of general KFTS-type SOE is only used to lock the light in SOE, and does not play a reflective role. We can make full use of the front end to achieve different results.

Usually, a semi-elliptical concentrator is added to the front end of the beam, which is called KOD-type SOE. However, due to a section of the SOE with one side round and one side square, it is difficult to process and it will form a circular spot at the same time. As mentioned earlier, it is important to make sure that each section is the same square. Generally, the front end receiver of SOE does not change much with the length / inclination angle. 10 mm is set here as the front-end length.
In order to better compare the performance of the new and ordinary KFTS-type SOEs, I make the volume of the new SOE approximately equal to that of the ordinary SOE.

![Figure 10. Hammer shaped SOE](image)

Figure 10 shows the stereogram of the new SOE. Figure 11 shows that there is little difference in the uniformity and light capture rate between the two, which confirms that the front-end part does not play a role in smoothing light.

![Figure 11. Irradiance distribution of the receiving plane with ordinary SOE and new SOE](image)

Figure 11 shows how the incidence angle affect the optical efficiency of the ordinary SOE and the new SOE. This new SOE has obvious advantages only when the deflection angle is large, but the general error angle is not so large. Therefore, this new SOE has advantages only under specific
requirements, which can be said to be a failed attempt. But this example shows that the conventional KOD-type SOE is based on the use of more materials and more complex processing conditions to obtain better results. If the same volume of materials are used, ordinary KFTS-type SOE has better performance in terms of both uniformity and light capture rate.

The front end of another new SOE designed has a groove whose inclination angle is approximately equal to the half diffusion angle of the light, so as to make the light as normal incidence as possible. According to Fresnel formula, the ratio of refracted light energy to incident light energy will be smaller, and the remaining space can expand the area of the incident plane to obtain greater light capture rate.

Figure 13 shows the stereogram of the quadrangular SOE with a groove. Figure 14 shows how the incidence angle affect the optical efficiency of the ordinary SOE and the new SOE. It can be seen that the deeper the groove is, the slower the decline is, but it begins to decline when the tracing error angle is smaller. The best overall effect is the groove depth of 1cm and 1.08cm, that is, the inclination angle of the groove is close to the half diffusion angle. In general, the new SOE achieves a larger acceptance angle under the same volume condition, and the uniformity of the new SOE is almost the same as that of the ordinary KFTS-type SOE.

4. Conclusions
In this paper, the uniformity of five different SOEs is compared, and the influence of their length or distance on the uniformity of irradiation surface is analyzed. It is confirmed that KFTS-type SOE is suitable for square photovoltaic cells. At the same time, two new SOEs based on KFTS-type SOE are
designed, and their influence on the receiving angle is analyzed. The first design is a failure for the general concentrating photovoltaic system, but the analysis shows that with the same amount of material, the common KFTS-type SOE is better than the KOD type SOE. In some papers, the conclusion that the KOD type SOE has a larger acceptance angle is not rigorous because more material is used. The second new SOE can significantly improve the receiving angle while using the same amount of material, which is a major innovation of this paper.

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