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Research and Design of Compound Fresnel Concentrator

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Abstract. An efficient and compact concentrator Fresnel concentrator is discussed and designed,The central region is a conventional Fresnel lens designed according to Snell's law of refraction,The edge region is designed to be TIR (internal total reflection) prism.According to the Fresnel formula,the best segmentation position and the optimum focal length of two kinds of lens are calculated,and use SolidWorks to build 3D model,The ray tracing simulation of the designed lens is carried out by using TracePro software.The results show that the efficiency is 89.6% and the F/# is 0.5 at high concentration. The efficiency of the traditional Fresnel concentrator is only 66% when the F/# is the same. The design goal of compact structure and high light performance is achieved.

1. Introduction

The third generation photovoltaic system often uses Fresnel lens as the concentrator [1]. In order to overcome the larger defect of traditional Fresnel F/# [2], this paper designs a compound Fresnel lens based on TIR-R Fresnel lens [3]. This paper through the establishment of mathematical model, theoretical analysis of composite Fresnel optimized design, achieving efficient and compact design purpose. the lens including total reflection and transmission center edge sawtooth sawtooth, through the derivation of optimal total reflection sawtooth position, determined a Fresnel condenser a total reflection sawtooth the optimal position of tooth exit surface reflection loss corresponding to the minimum, and calculated on the basis of the maximum transmittance of focal size, finally using Monte Carlo ray tracing method on the condenser system in the simulation analysis, the analysis results show that the lens can be in high concentration when the concentration efficiency of condenser system close to 90%, the F/# is 0.5.

2. Design method

2.1. Fresnel lens

Figure 1 is a schematic diagram [4] that converges to the focus after the light passes through the lens. The distance between the center of the i ring center and the center of the lens is hi. The parallel light is incident from the middle point M of the i ring.Because the light is incident perpendicularly, it does not deflect at the M point. When the light passes through the lens and reaches the N point of the lens, the light is not vertical to the surface of the shot, and the deflections occur at this time. The angle of the i girdle is the angle between the light and the optical axis when it converges to the focal point, and it is also the deflection angle of the light. The incidence angle is i1 and the exit angle is i2. The geometric relationship and the law of refraction from the angle.

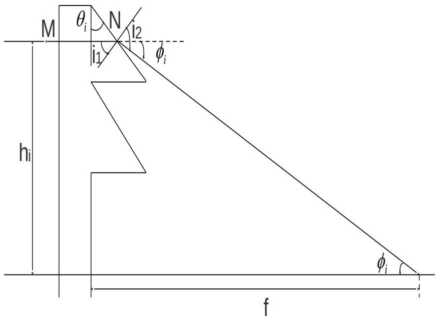

Figure 1. Schematic diagram of Finel lens.

$$i_2 = i_1 + \phi_i \tag{1}$$

$$\theta_i = i_1 \tag{2}$$

$$n \cdot \sin i_1 = \sin i_2 \tag{3}$$

$$\tan \phi_i = \frac{h_i}{f} \tag{4}$$

$$\tan \theta_i = \tan i_1 = \frac{\sin \phi_i}{n - \cos \phi_i} \tag{5}$$

2.2. The design method of TIR prism in the edge region

Figure 2 is a schematic diagram that converges to the focus after the light passes through a fully reflective lens. The distance between the center of the i band and the center of the lens is hi. The parallel light is incident perpendicularly from the plane of the fully reflective lens plane. The parallel light is incident from the middle point M of the i ring.

Because the light is perpendicular to the incident, the M is not deflected when the light passing through the lens to the lens N point, light total reflection occurs when the reflected light through the lens to the lens and the outgoing line time point P are not perpendicular to the surface, the deflection at. The angle of the i ring surface is the angle between the light and the optical axis when the light converges to the focal point. The total angle of incident light is i_1, the incidence angle is i_{1}`, and the exit angle is i_2. The geometric relationship and the law of refraction can be obtained from the angle.

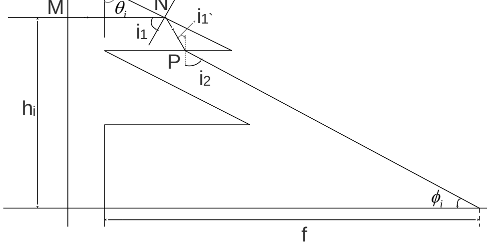

Figure 2. Schematic diagram of total reflection lens

$$\sin i_{1^{`}} = \frac{\sin(90-\phi_i)}{n} = \frac{\cos(\phi_i)}{n} \tag{6}$$

$$i_1 = \frac{\arcsin(\frac{\cos(\phi_i)}{n})+90}{2} \tag{7}$$

3. The calculation model of the main parameters

3.1. The calculation of the optimal position of the fully reflected sawtooth

According to formula (5), from the center of the Fresnel lens to the edge, with the increase of sawtooth angle (θ_i), the incident angle i1 of the sun beam on the saw tooth increases synchronously. According to the formula (1) (4) and combined with the total reflection formula

$$n \cdot \sin i = \sin\frac{\pi}{2} \tag{8}$$

The relation formula of the half caliber of the Fresnel lens and the focal length f can be derived

$$h_{\max} = f\sqrt{n^2-1} \tag{9}$$

According to the formula of transmittance (15), the reflection loss will increase sharply and the transmittance of light decreases sharply when it is near the total reflection angle. Therefore, the half caliber will not be designed to the maximum theoretical value, and the ratio of height to width is usually greater than 1. In order to further increase the caliber of the Fresnel concentrator, a fully reflective tooth structure is generally used instead of the transmission saw tooth. However, the Fresnel reflection loss also occurs on the total reflection sawtooth's exit surface, and the closer to the center of Fresnel concentrator, the more serious the reflection loss is.

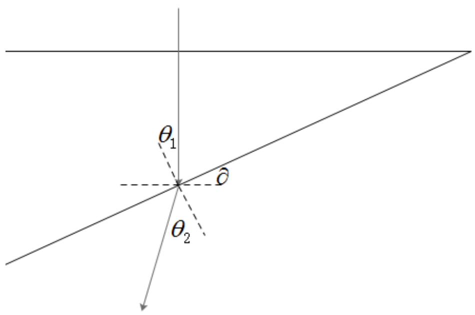

Figure 3. Schematic diagram of transmittance calculation.

The formula for amplitude ratio of transmitted light is

$$t_s = \frac{2n_1 \times \cos\theta_1}{n_1 \times \cos\theta_1 + n_2 \times \cos\theta_2}$$
$$t_p = \frac{2n_1 \times \cos\theta_1}{n_2 \times \cos\theta_1 + n_1 \times \cos\theta_2} \tag{10}$$

Formula of transmittance

$$\tau_s = \frac{n_2 \cos\theta_2}{n_1 \cos\theta_1} t_s^2$$
$$\tau_p = \frac{n_2 \cos\theta_2}{n_1 \cos\theta_1} t_p^2 \tag{11}$$

Transmissivity T

$$T = \tau_s \times \tau_p \times T_b \tag{12}$$

The Tb is the transmission factor of the lens material.

According to the Fresnel formula, the magnitude of the reflection loss is directly related to the incidence angle i at the exit of the sawtooth, no matter what the reflection loss occurs in the transmission saw tooth or the total reflection loss in the saw tooth. Therefore, what only should do is to find such a critical position to satisfy the equal incidence angle at the sawtooth exit surface at this location, which is equivalent to its Fresnel reflection loss. So the problem is simplified to solve the problem of equal angle of incidence at the surface of the saw tooth. The angle of incidence at the ejection surface of the two lenses can be calculated by the formula (5) (6). In Figure 4, the blue curve is a transmission saw tooth, and the red curve is a fully reflected saw tooth.From the graph, we can see that with the increase of $\tan\phi_i$, the total loss of the transmission saw tooth increases, and the total reflection loss of the total reflection saw tooth decreases. If the $\tan\phi_i$ =0.5 around (lens material is PMMA, the index of refraction n=1.489), the two kinds of sawteeth have the same incident angle, namely the reflection loss is the same. This intersection is the critical position required.

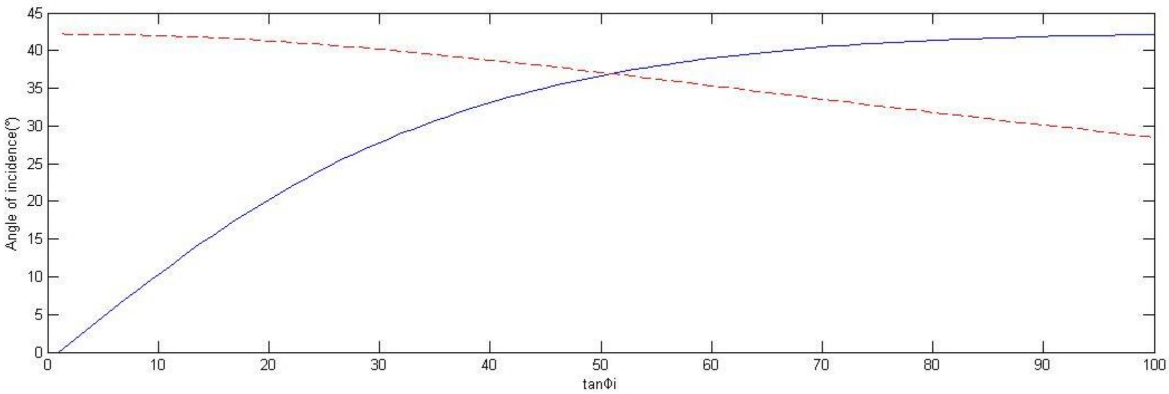

Figure 4. The change of the incident angle with the convergence angle Øi at the sawtooth exit plane

3.2. A mathematical model of the efficiency of the spotlight

According to Figure 5, the vertical incident light total reflection sawtooth point P by T refraction, just through the bottom of the sawtooth, the AP incident light can converge to the focal point, and the PB incident light with serrated occlusion, unable to reach the focus position, causing great loss.

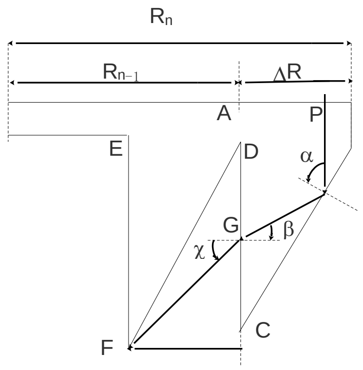

Figure 5. Schematic diagram of total reflection sawtooth

Actual incidence of single sawtooth

$$\eta_i = T_i \times S_i, i = 1,2,3,..n \tag{13}$$

Total efficiency

$$\eta_{\text{Total}} = \sum_{i=1}^{n} \eta_i, i = 1,2,3,..n \tag{14}$$

T_i is the transmissivity of the i sawtooth, S_i is the effective incidence area of the i sawtooth, and the n is the total number of saw teeth.

$$S_i = [(AP + R_{n-1})^2 - (R_{n-1})^2] \times \pi \tag{15}$$

$$\text{AP} = \text{GC} \times \cos(\beta) \tag{16}$$

$$\text{GC} = \Delta R \times \tan(\chi) - (EF - DC) \tag{17}$$

$$\chi = \arcsin(\text{n} \times \sin(\beta)) \tag{18}$$

$$\beta = 2\alpha - 90^\circ \tag{19}$$

As shown in Figure 6, the increase of focal length from 100mm to 200mm has no obvious change in transmittance, but when the focal length is less than 100mm, the transmittance decreases obviously. Therefore, this paper selects 100mm as the focal length of the lens, which can not only guarantee efficiency, but also reduce the ratio of height to width.

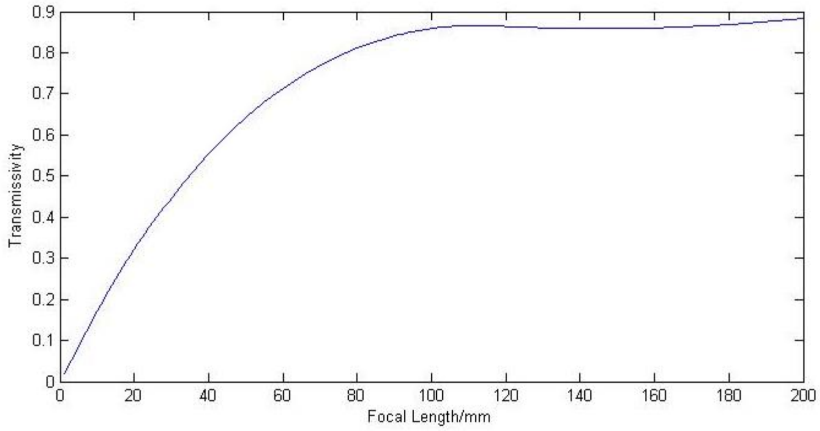

Figure 6. The relation curve of focal length and transmissivity

3.3. 3D modeling

Table 1. Design data

Rings	Sawtooth angle/°	Rings	Sawtooth angle/°	Rings	Sawtooth angle/°	Rings	Sawtooth angle/°	Rings	Sawtooth angle/°
1	1.17	11	21.93	21	33.93	31	62.58	41	60.81
2	3.5	12	23.54	22	34.7	32	62.4	42	60.64
3	5.81	13	25.05	23	35.41	33	62.22	43	60.47
4	8.08	14	26.46	24	36.06	34	62.04	44	60.3
5	10.3	15	27.78	25	36.66	35	61.86	45	60.13
6	12.45	16	29.01	26	63.45	36	61.69	46	59.97
7	14.53	17	30.15	27	63.28	37	61.51	47	59.81
8	16.52	18	31.21	28	63.11	38	61.33	48	59.64
9	18.42	19	32.19	29	62.93	39	61.16	49	59.48
10	20.22	20	33.1	30	62.75	40	60.98	50	59.33

Using the design data in Table 1, the 3D model of the concentrator is established by the 3D graphics software SolidWorks. The radius is 100mm, the annular distance is 2mm, the focal length is 100mm, the number of sawtooth in the central area is 25 rings, the edge total reflection saw tooth is 25 rings, F/# is 0.5.

4. Result analysis and conclusion

Figure 7, figure 8 is a ray tracing map of a composite Fresnel lens and a traditional Fresnel lens. The red light attenuation represents to the original 100% ~ 66%, the green line represents the attenuation to the original 66% to 33%, the blue line represents the attenuation to the original 33% to 0%. From the graph, the new Fresnel concentrator makes most of the light gathered in the focal plane, and only a small amount of energy is lost. However, only a small amount of light is gathered in the focal plane of the traditional Fresnel concentrator, and most of the energy is lost.

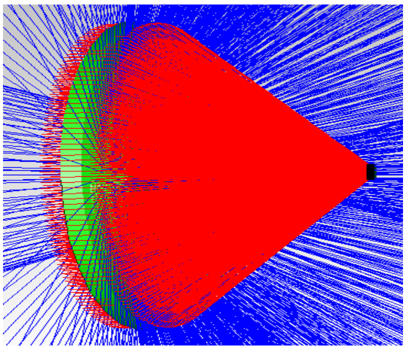

Figure 7. Ray tracing diagram of Fresnel lens

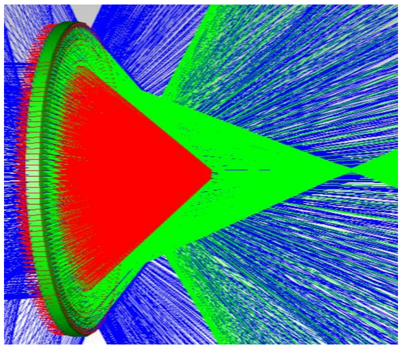

Figure 8. Ray tracing diagram of compound Fresnel

Figures 9 and 10 are the focal plane irradiance graphs of the compound Fresnel concentrator and the traditional Fresnel concentrator, respectively. From the chart, we can see that the efficiency of the compound concentrator is close to 90%, while the Fresnel concentrator efficiency is only 66%.

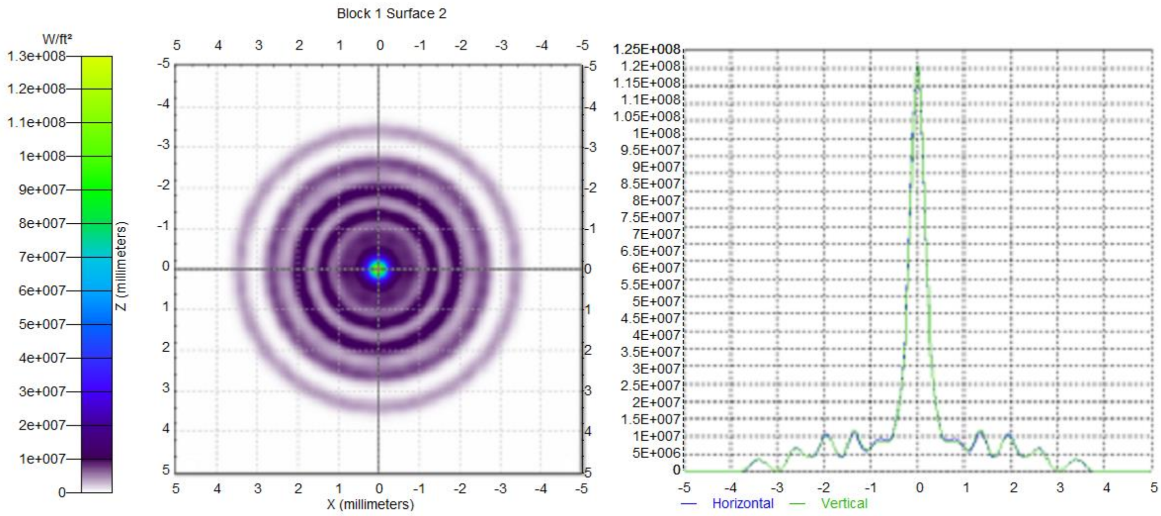

Figure 9. Focal plane radiation patter of compound lens

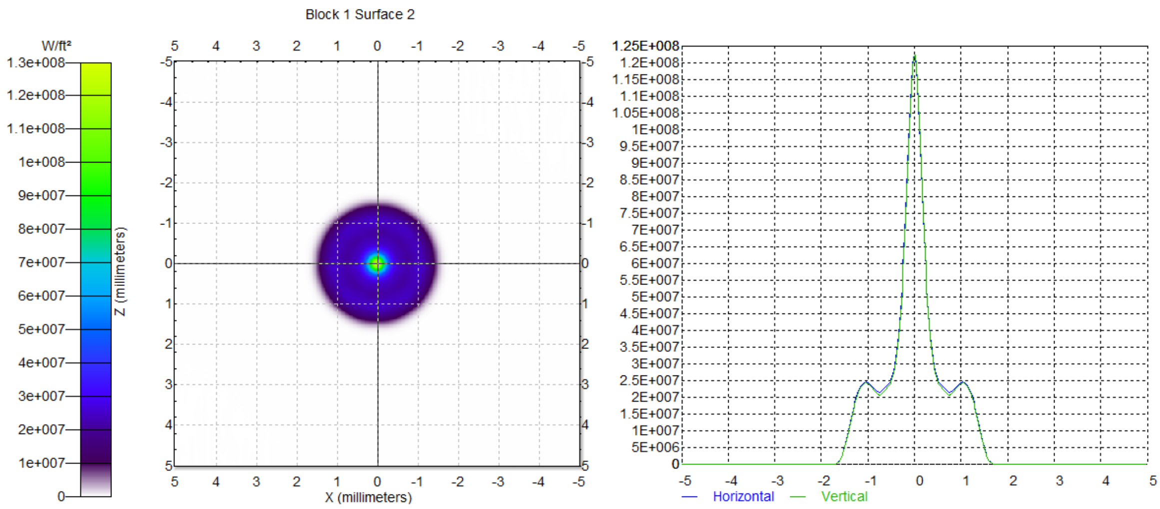

Figure 10. Focal plane radiation pattern of Fresnel lens

In this paper, in order to improve the efficiency of photovoltaic concentrator system, at the same time of high magnification, it can have a smaller F/#, according to the Fresnel formula, through the calculation and analysis, we get the advantages and disadvantages of the total reflection saw tooth and the refraction saw tooth. After mathematical modeling and simulation, we design a high energy efficient compact structure solar concentrator. Through the simulation analysis of ray tracing, the efficiency of the spotlight is up to 89% and the ratio of diameter to length is 0.5. It provides a design idea for the design of portable photovoltaic devices used in the field.

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