IOP Conf. Series: Earth and Environmental Science **69** (2017) 012177 doi:10.1088/1755-1315/69/1/012177

Design and experimental study on Fresnel lens of the combination of equal-width and equal-height of grooves

Limin Guo [1], Youqiang Liu [1], Rui Huang [1] and Zhiyong Wang[1,*]

[1]Beijing University of Technology, Institute of Laser Engineering, Beijing, China, 100124

*Zhiyong Wang, e-mail: zywang@bjut.edu.cn

Abstract: High concentrating PV systems rely on large Fresnel lens that must be precisely oriented in the direction of the Sun to maintain high concentration ratio. We propose a new Fresnel lens design method combining equal-width and equal-height of grooves in this paper based on the principle of focused spot maximum energy. In the ring band near the center of Fresnel lens, the design with equal-width grooves is applied, and when the given condition is reached, the design with equal-height grooves is introduced near the edges of the Fresnel lens, which ensures all the lens grooves are planar. In this paper, we establish a Fresnel lens design example model by Solidworks, and simulate it with the software ZEMAX. An experimental test platform is built to test, and the simulation correctness is proved by experiments. Experimental result shows the concentrating efficiency of this example is 69.3%, slightly lower than the simulation result 75.1%.

1. Introduction

Optical concentration provides strong cost leverage for high-efficiency photovoltaic (PV) cells[1]. High concentrated photovoltaic technology uses relatively inexpensive optics such as mirrors and lenses to concentrate sunlight from a broad area into a much smaller area of active semiconductor cell, and converts sunlight directly to electricity[2]. Concentrator is a critical part of HCPV module. At present, there are two types of HCPV module concentrator, transmission type and reflection type. The transmission type concentrator is usually Fresnel lens. It has been widely used in the concentrated photovoltaic field, with the advantages of simple structure, light weight, low cost, easy processing, etc[3]. High concentrating PV (HCPV) systems rely on large Fresnel lens that must be precisely oriented in the direction of the Sun to maintain high concentration ratio.

In order to ensure the high photoelectric conversion efficiency of the concentrated module, the design of Fresnel lens is studied. Akisawa Atsushi, et al., studied Fresnel lens, and proposed a method to design a dome-shaped Fresnel lens [4]. Daniel, et al., designed a multi-point focus Fresnel lens to improve the uniformity of the light concentrator [5]. K. Ryu, et al., designed a modular small area of Fresnel lens. Through data simulation, the traditional flat Fresnel lens is divided into a number of a small area. So that the solar energy can be uniformly incident to the solar cell, and the uniformity of the focusing spot is increased by using the solar energy of different small region[6]. Pu Cong, et al., designed Ultra-thin fold complex Fresnel concentrator, whose focal length is 30mm[7]. Li Peng, et al., according to the structural design of the curved base Fresnel lens, through the derivation of the different prismatic conditions to obtain unified design formula of Fresnel lens structure design[8]. The above researches are mainly focused on the theoretical design, and the research on the practical application is less. Germany's Fraunhofer Solar System Research Institute studied Fresnel lens. This

Research Institute and Solar FLATCON company jointly developed the Concentrix spotlight module products[9]. Concentrated module products can achieve the highest 500X concentration, the optical efficiency of curved Fresnel lens reach to 78%-82%. But Fresnel lens is curve, difficult to process.

In this study, a Fresnel lens design method combining equal-width and equal-height of grooves is firstly proposed on the principle of focused spot maximum energy, which avoid a lot of deficiencies in the application of the curved Fresnel lens. In the ring band near the center of Fresnel lens, the design with equal-width grooves is applied, and when the given condition is reached, the design with equal-height grooves is introduced near the edges of the Fresnel lens, which ensures all the lens grooves are planar. In this paper, we establish a Fresnel lens design example model by Solidworks, and simulate it with the software ZEMAX. An experimental test platform is built to test.

2. Fresnel lens design of the combination of equal-width and equal-height of grooves

Fresnel lens design method combining equal-width and equal-height of grooves is firstly proposed in this paper based on the principle of focused spot maximum energy. Since Fresnel lens is a rotational symmetric structure with the optical axis as the center.

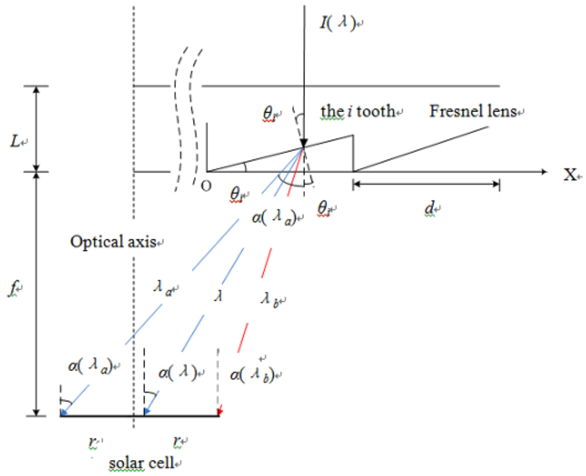

Figure 1. Design schematic diagram of Fresnel lens

The converging optical path of the Fresnel lens is shown in figure 1. The Fresnel lens groove tip of the i groove is the origin of O. The focal length of the Fresnel lens is f , and the thickness of the Fresnel lens is L . The natural light ($I_{AM1.5D}$) is incident from the i groove, incident on the lens surface vertically. The groove inclination is θ_i, and the angle of incidence is θ_i. The incident light is dispersed through the Lens lower serrated surface. Suppose that the shortest wavelength of light λ_a incident to the left point(a) of the solar cell, intersection with the X axis is x, and the angle between the optical axis is $\alpha(\lambda_a)$.The longest wavelength of light λ_b incident to the right point(b) of the solar cell, intersection with the X axis is x, and the angle between the optical axis is $\alpha(\lambda_b)$. The length of solar cell is $2r$. The light wavelength between λ_a and λ_b are gathered to the solar cell surface, λ is a discretional incident light wavelength.

The working surface of lens made up of several rings, for the convenience of description, the center ring known as the first ring, from the center to the edge along the X-axis direction, the ring sequence numbers in ascending order. Suppose before the N-1 ring use the equal-width groove design and the groove width is d. Starting from the N ring, the other grooves use the equal-height groove design. Incidence angle of the N-1 ring is θ_{N-1}, and incidence angle of the N ring is θ_N, then

$$\begin{cases} \tan\theta_N > \dfrac{L}{d} \\ \tan\theta_{N-1} \le \dfrac{L}{d} \end{cases} \tag{1}$$

After using the groove height design, groove width becomes variable, The *i* ring of the groove width (d_i) can use represented by piecewise functions:

$$d_i = \begin{cases} d & i < N \\ \dfrac{L}{\tan\theta_i} & i \geq N \end{cases} \tag{2}$$

By the law of refraction and the geometrical optics, we gain:

$$n(\lambda_a)\sin\theta_i = \sin(\theta_i + \alpha(\lambda_a)) \tag{3}$$

$$\tan\alpha(\lambda_a) = \frac{\sum_{n=1}^{i} d_n + r + x}{f} \tag{4}$$

In the formula (3) - (4), for the *i* groove, $\alpha(\lambda_a)$ and *x* is unknown, other parameters are known. On the *i* groove, λ_a and λ_b are functions of *x*. The light ($I_{AM1.5D}$) is incident from the *x* point. After lens, the total energy *E*(x) of the solar cell is:

$$E(x) = \int_{\lambda_a(x)}^{\lambda_b(x)} T I_{AM1.5D} d\lambda \tag{5}$$

In formula (5), *T* is the transmittance of the *i* groove. Due to thin thickness of the Fresnel lens, the absorption of the material loss is neglected, so we only consider the reflection loss of the incident sunlight in the groove. Light λ from Fresnel lens of the *i* groove into the air, the incident Angle is θ_i, the Angle of Refracted light and the optical axis is $\alpha(\lambda_a)$. From Fresnel formula, *s* components and *p* components of the incident light at the interface transmission rate can be expressed as:

$$\begin{aligned} T_s &= \frac{\sin 2\theta_i \sin(2\theta_i + 2\alpha(\lambda))}{\sin^2(2\theta_i + \alpha(\lambda))} \\ T_p &= \frac{\sin 2\theta_i \sin(2\theta_i + 2\alpha(\lambda))}{\sin^2(2\theta_i + \alpha(\lambda))\cos^2(\alpha(\lambda))} \\ T &= \frac{T_s + T_p}{2} \end{aligned} \tag{6}$$

We will bring the formula (6) into the formula (5), the total energy $E(\theta_i)$ though the *i* groove to reach the solar cell receiving surface, is

$$E(\theta_i) = \int_0^{d_i} \int_{\lambda_a(x)}^{\lambda_b(x)} \frac{\dfrac{\sin 2\theta_i \sin(2\theta_i + 2\alpha(\lambda))}{\sin^2(2\theta_i + \alpha(\lambda))} + \dfrac{\sin 2\theta_i \sin(2\theta_i + 2\alpha(\lambda))}{\sin^2(2\theta_i + \alpha(\lambda_k))\cos^2(\alpha(\lambda))}}{2} I_{AM1.5D} d\lambda dx \tag{7}$$

The formula (9) gives the relationship between $E(\theta_i)$ and θ_i. In order to obtain the maximum solar radiation energy value of the solar cell receiving surface, combining with the Fresnel lens actual processing capacity of grooves inclination angle in the range of 0°~ 45°, we make numerical calculation with 0.1° step size. We can obtain the *i* groove inclination angle θ_i when $E(\theta_i)$ is maximum, so as to determine parameters of the entire Fresnel lens.

3. Fresnel lens examples of the combination of equal-width and equal-height of grooves

In practical engineering applications, the plate Fresnel lens generally need to be molded, but it is more difficult to process. a non-uniform thickness design Fresnel lens. Fresnel lens design method combining equal-width and equal-height of grooves is proposed in this paper, in order to make sure all the working face of the Fresnel lens is flat, and greatly reduce the complex manufacturing process.

3.1. Fresnel lens Modeling

IOP Conf. Series: Earth and Environmental Science **69** (2017) 012177 doi:10.1088/1755-1315/69/1/012177

The area of solar cell is $2.5 \times 2.5\text{mm}^2$, the area of the lens is $50 \times 50\text{mm}^2$, concentrating ratio is set to 400 times, and Focus of Fresnel lens is set to 93.5mm. Fresnel lens substrate is a ultra-white glass with a thickness of 3.2mm. The lens material is the silicone with thickness of 1mm. Design at room temperature. The center ring working face of the lens is plane, the sun light is perpendicular to the incident, does not produce refraction. Considering the factors such as machining process, mounting process, high and low temperature deformation, the center circle diameter is 2mm, that is, the groove width is 1mm. Since second rings, the equal-width groove design is used. When the equation (2) is satisfied, the equal-height groove design is used.Prong coordinates, inclination angle and other parameters of the ring from the second to the last saw groove are solved by the formula (1) to (4), (7) by Matlab. The relationship between groove ordinal i with groove inclination angle θ_i of Fresnel lens shown in Figure 2. As shown in Figure 3, the Fresnel lens calculated parameters was imported in Solidworks in order to make 3D model.

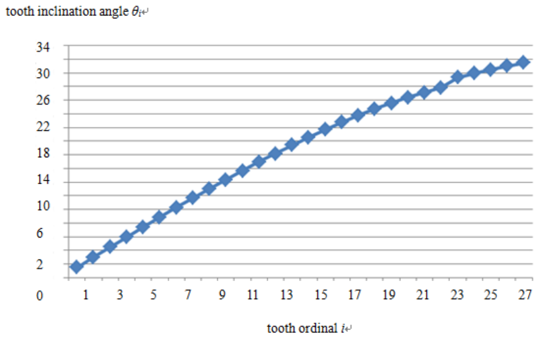

Figure 2. The relationship between groove ordinal i lens with groove inclination angle θ_i

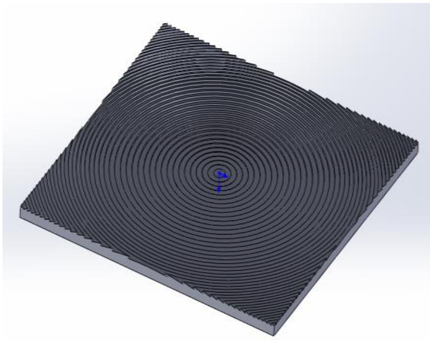

Figure 3. The 3D model of Fresnel

3.2. Optical simulation and analysis

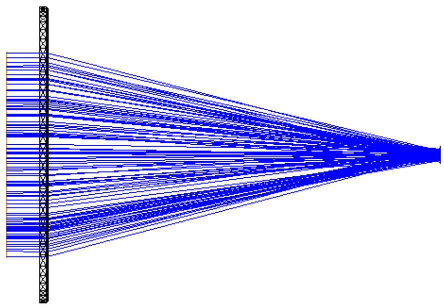

Figure 4. The concentrating effect of Fresnel lens

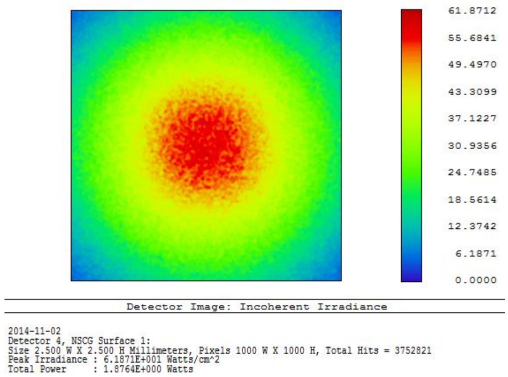

Figure 5. The energy distribution of focal spot on the solar cell surface

The 3D model of the Fresnel lens was introduced into the Zemax for computer simulation. We set the source parameters on the basis of the AM1.5D, and set Lens material parameters on the basis of parameters of the silicone material . The solar radiation is set to 1000W/m^2, the standard intensity. Solar cell receiving surface is $2.5 \times 2.5\text{mm}^2$. Fig.4 shows the concentrating effect of Fresnel lens (the image clear, only part of the light). Fig.5 shows the energy distribution of focal spot on the solar cell surface.

These parameters are determined by optical simulation.

Concentrating efficiency of Fresnel lens $\eta = {}^{1.8764}\!/_{2.5} = 75.1\%$. Concentrating efficiency of this design is high under the condition of AM1.5D full spectrum simulation.

Energy uniformity of the beam spot $U = \frac{E_{max} + E_{min}}{2E_{max}} = \frac{18.561 + 61.871}{2 \times 61.871} = 0.65$. The U of Fresnel lens needs to be further improved.

Geometric concentration ratio of Fresnel lens C ≈ 400, F number is 1.87.

4. Experimental study of Fresnel lens design of the combination of equal-width and equal-height of grooves

According to various determined parameters of the Fresnel lens, we made a Fresnel lens unit. Material object is showed in Fig.6. We built an experimental test platform, which has an independent power generating unit. Fig.7 show that the platform includes a Fresnel lens unit, solar cell, precise adjustment stage with three freedoms, mounting bracket and associated fixtures and the like. The adjustment stage with three freedoms, the plane determined by X-axis and Y-axis is parallel with the Fresnel lens unit, and Z-axis direction is perpendicular to the Fresnel lens unit as the focal length direction. In the experiment, the X axis and Y axis directions are moved to adjust the platform to ensure that the focusing spot is the center of the solar cell, and then the Z axis direction is moved to ensure that the ideal spot is focused on the receiving surface of the solar cell. The efficiency of solar cells is 40%, which is producted by Redsolar New Energy Technology Co. Ltd., under the premise of the German ISE Fraunhofer. We tested the IV performance in the concentrating module test system, with light intensity of 850W/m^2.

The maximum output power P_{max} of power generating unit were tested 10 times. The test results are shown in Table 1.

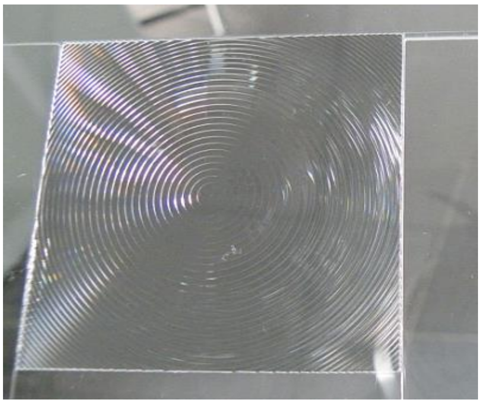

Figure 6. A processed Fresnel lens unit

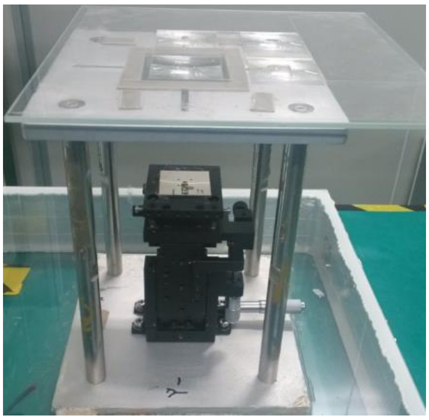

Figure 7. The experimental platform of Fresnel lens I-V test

Table 1. Test results of output power

times	1	2	3	4	5	6	7	8	9	10
$P_{max:/}$W	0.592	0.590	0.585	0.592	0.587	0.588	0.591	0.589	0.593	0.583

Results analysis: according to the test results that the average value of the maximum output power P_{max} is 0.589W. Fresnel lens unit area is 50×50mm^2, the intensity of the solar simulator is 850W/m^2 and solar cell photoelectric conversion efficiency is 40%, so we can conclude the concentrating efficiency of the Fresnel lens unit is 69.3%, which is less than the theoretical value of the concentration efficiency of 75.1%. The loss is mainly derived from the reflection and scattering loss of the interface, the difference of the actual machining precision and theoretical accuracy of Fresnel lens size and surface shape, the difference of actual transmittance and the transmittance of the theory, the position error of Fresnel lens and solar cell, and so on.

5. Conclusion

The paper shows that a planar Fresnel lens design method combining equal-width and equal-height of grooves is firstly proposed based on the principle of focused spot maximum energy maximization principle. Using the non-imaging optics and the mathematical theory, the mathematical model of the energy on the receiving surface of the solar cell is established. According to the model, the parameters of Fresnel lens are given and the Solidworks model is established. And the 3D model of the Fresnel lens is imported into Zemax software. The case of the Fresnel lens with a vertical incidence of the sun's rays is simulated. The simulation results show that the main performance parameters and the Fresnel lens concentrating efficiency, the energy uniformity of the focusing spot, the concentration ratio and the F number are analyzed. According to the design parameters, the Fresnel lens unit is produced, and the actual parameters of the lens unit are tested. The measured parameters are in good agreement with the simulation results, which proves the correctness of the simulation results.

Fresnel lens designed by the method is easily processed, has good optical performance, and breaks the limit of concentrating times which provides experiment basis for engineering applications of the Fresnel lens applied in high concentrating photovoltaic modules. But the receiving angle and the influence of temperature have not been analyzed in this paper, which will be studied in the following articles. Although the concentrating efficiency of this design is high, there is room for improvement. Therefore, the following article will design suitable secondary optical components to further improve the concentration efficiency.

References

[1] Jared S. Price, Xing Sheng, Bram M. Meulblok, John A. Rogers and Noel C. Giebink 2015 *J. Nat. Commun*, DOI: **10.1038**, 7223.

[2] Coughenour, BM., Stalcup, T., Wheelwright, B., Geary, A., Hammer, K. and Angel, R. 2014 *J Opt. Express*, **22**, A211–24.

[3] Xie, W. T., Dai, Y. J., Wang, R. Z. and Sumathy, K., 2011 *J. A review. Renew, Sust. Energ*. **15**, 2588–606.

[4] Atsushi Akisawa, Masao Hiramatsu and Kouki Ozaki, 2012 *J. Solar Energy,* **86(3)**, 877–85.

[5] D Vazquez-Molini, E Bernabeu, JMDL Climente, A Domingo-Manrique and Angel Garcia-Botella, 2009 *Proc. SPIE* **7407**, 01.

[6] K. wangsun Ryu, Jin- Geun Rhee, Kang-Min Park and Jeong Kim, 2006 *J. Solar Energy*, **80(12)**, 1580–87.

[7] PIAO Cong and ZHANG Guoyu, 2011 *J. Appl Optics,* **32(1)**, 23–26.

[8] LI Peng, WU Heli and YANG Peihuan, 2010 *J WUHAN UNIV TECHNOL*, **32(6)**, 62–66.

[9] Tobias Gerstmaier, S.V.R., Andreas Gombert, André Mermoud and T.L. Eric, 2010 Freiburg, Germany presented at the 6th International Conference on Concentrating Photovoltaic Systems (CPV-6), 7–9.