Design and analysis of a new toroidal Finel lens for three junction GaAs battery

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Abstract

The traditional annular Fresnel lens using single wavelength design, focus on the design of focal plane uniform distribution, in the design of the wavelength of the light incident has better uniformity, but the sun light dispersion phenomenon after the incident, the greater the closer to the lens edge region of focal spot width, leads to the focal plane of the uneven distribution of energy. A lot of light to the outside, and with the focal length decreases, the uniformity will be further reduced. Therefore,this paper is of wide spectral absorption,respectively GaInP/GaInAs/Ge multi junction solar cell, considering the dispersion curves of refraction and lens material spectral response rate in each sub cell, the torus focal spot improved design method and multi wavelength combination design, optimize the design of the Fresnel lens. The simulation results show that the concentration uniformity reaches 82% while the concentrating efficiency reaches 80% in the range of 0.3 μm-1.8 μm。

Keywords

Optical device design;torus Fresnel Lens ;Uniformity;non imaging optics.

1. Introduction

The third generation photovoltaic system is composed of four parts: concentrator, photovoltaic cell, day-to-day system and radiator. It increases the incident energy on the surface of photovoltaic cell by concentrator, so that the photovoltaic system can obtain high efficiency output while reducing the required area of photovoltaic cell, reducing the cost of power generation [1,2], and has broad prospects for development. Because the point-focused Fresnel lens based on single-wavelength design is widely used in concentrating photovoltaic system, there are many technical problems such as low utilization rate of photovoltaic cells and uneven irradiation, which make the surface of photovoltaic cells overheat locally, cause cell damage, reduce photoelectric conversion efficiency and increase the cost of power generation [3]. In order to improve the irradiation uniformity, the secondary concentrator is usually used, but it will increase the line loss and cost, and make the mechanical structure more complex.

In order to improve the above problems, a new toroidal Fresnel lens for GaInP/GaInAs/Ge multi-junction solar cells is designed in this paper. PMMA resin is selected as the lens material. Considering the distribution of solar broad spectrum irradiation, the dispersion characteristics of PMMA materials and the spectral response characteristics of three-junction GaAs cells, the traditional design method of toroidal Fresnel lens is improved. The lens is divided into several main wavelengths to design, the focus distribution is changed, and the problem of optimum design parameters selection is solved by using the improved particle swarm optimization algorithm. The design objectives are as follows: the concentrating efficiency of the lens reaches 80%, the irradiation uniformity reaches 74%, and the geometric concentrating ratio is more than 300 times under the spectral response bands of GaInP/GaInAs/Ge battery and AM1.5D standard sunlight.

2. Calculating Method of Main Optical Parameters of Lens

2.1 Mathematical Model of Concentrating Efficiency

The optical loss of Fresnel lens can be roughly divided into five categories: reflection loss, absorption loss, technological loss, structural loss and truncation loss. Reflection loss and truncation loss are the main causes of optical loss.

As shown in Fig. 1, when a broad-spectrum light source is incident, the received band of photovoltaic cells is only lambda λ_s~λ_l ambda λ_l due to the dispersion phenomenon, and the received radiation energy is called truncation loss.

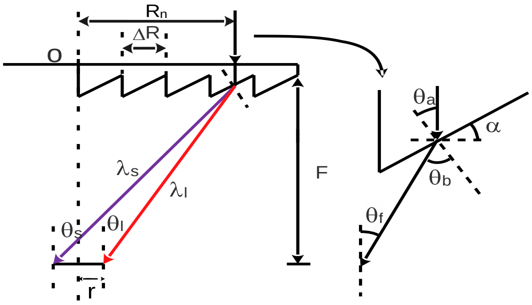

Fig.1 Schematic diagram of the principle of truncation

Truncated wavelength can be calculated by the following formula

$$\partial = \arctan\left(\frac{\sin(\arctan R_n / F)}{n_m - \cos(\arctan R_n / F)}\right) \tag{1}$$

$$n_l \sin\partial = \sin(\theta_l + \partial) \tag{2}$$

$$n_s \sin\partial = \sin(\theta_s + \partial) \tag{3}$$

$$n = a + b\lambda^2 + c\lambda^{-2} + d\lambda^{-4} + e\lambda^{-6} + f\lambda^{-8} \tag{4}$$

According to formula (1) ~ (3), the refractive index NL and NS corresponding to wavelength lambda λ_l and lambda λ_s can be obtained. Among them, NM is the main wavelength used in the design of the single tooth, and then the critical wavelengths of lambda λ_l and lambda λ_s are calculated according to Schoot formula (4).

Reflection loss can be calculated by Fresnel formula.

$$t_s = \frac{2n_a \times \cos\theta_a}{n_a \times \cos\theta_a + n_b \times \cos\theta_b}$$
$$t_p = \frac{2n_a \times \cos\theta_a}{n_b \times \cos\theta_a + n_a \times \cos\theta_b} \tag{5}$$

The transmittance formula is

$$\tau_s = \frac{n_b \cos\theta_b}{n_a \cos\theta_a} t_s^2$$
$$\tau_p = \frac{n_b \cos\theta_b}{n_a \cos\theta_a} t_p^2 \tag{6}$$

The transmittance T is

$$T = \tau_s \times \tau_p \times T_b \tag{7}$$

Tb is the transmission factor of lens material.

Considering both truncation loss and reflection loss, the single-tooth focusing efficiency is as follows

$$\eta_i = \frac{E_i}{E_s} = \frac{\int_{\lambda_s}^{\lambda_l} E_{in}(\lambda)\times T(\lambda)d\lambda}{\int_{300}^{1800} E_{in}(\lambda)\times T(\lambda)d\lambda} \tag{8}$$

In the formula Ei is the sum of the radiation energy transmitted to the solar cell by different wavelength light on the first single tooth, Es is the radiation energy of the first single tooth light on the surface of the lens, and Ein (λ) is the radiation energy of the incident light with the wavelength of λ.

Then the total radiation efficiency of the lens to the solar spectrum is

$$\eta_{总} = \sum_{i=1}^{n} \eta_i \cdot S_i, i = 1,2,3,\ldots n \tag{9}$$

In the formula, Si is the area of the first serrated tooth and N is the total number of serrated teeth.

2.2 Calculation Model of Focal Spot Spatial Uniformity of Toroidal Fresnel Lens

The focal plane is divided into y regions based on the midpoint of the photocell. The width of a single wavelength light transmitted through a single serrated surface falls on the focal plane is S, so any wavelength refracted by the serrated surface falls into one or more regions. As shown in Figure 2, the light rays are refracted and then fall into the X and x+1 regions.

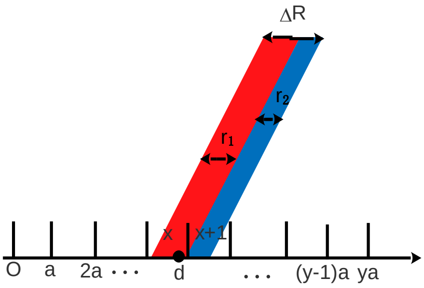

Fig2. Calculation model of spatial uniformity of focal spot

Firstly, the nth single tooth inclination angle a is determined according to formula (1). When the wavelength of incident light is lambda, the coordinates of the light falling point are determined according to formula (10):

$$\mathrm{d} = R_n - \tan(\arcsin(\sin\partial)\times n_\lambda - \partial)\times \mathrm{F} \tag{10}$$

The area where the landing point belongs x is

$$x = \left\lceil \frac{d}{a} \right\rceil \tag{11}$$

The area where the landing point belongs x is

$$E_x = \frac{E(\lambda)\times T_{n\lambda}\times r_1 \times (2R_n - S + r_1)}{r_1 \times (2\times a \times x - r_1)} \tag{12}$$

$$E_{x+1} = \frac{E(\lambda)\times T_{n\lambda}\times r_2 \times (2R_n + S - r_2)}{r_2 \times (2\times a \times x + r_2)} \tag{13}$$

E(λ) is the radiation energy of the incident light, and the transmittance of the light with wavelength λ travels through the nth single tooth.

By calculating the energy distribution in each region of the focal plane after the refraction of 0.3-1.8 micron light on all sawtooth, the uniformity of the concentration distribution is measured by the maximum and average of the intensity of light.

The mean value of irradiance distribution on the output surface is defined as follows

$$E_{AVE} = \frac{1}{y}\sum_{x=1}^{y} E_x \tag{14}$$

The uniformity of concentration distribution can be expressed as

$$\Delta E = \left(1 - \frac{E_{\mathrm{MAX}}}{E_{AVE}}\right) \times 100\% \tag{15}$$

3. Optimal design of new toroidal Fresnel lens

3.1 Considerations for Optimum Design

The new toroidal Fresnel lens is mainly designed according to PMMA silica gel dispersion characteristics, AM1.5D solar spectral characteristics and spectral response characteristics of GaInP/GaInAs/Ge multi-junction solar cells, so that each junction solar cell can obtain higher radiation uniformity and larger effective radiation energy.

The dispersion characteristics of PMMA materials can be obtained from Schoot formula in Section 2.1. The specific parameters are shown in Table 1.

Tab1 Schoot coefficient

a	b	f
1.48038155	-0.0003265	-0.0000037
c	d	e
0.00416666	-0.0002904	0.00007254

Figure 3 shows the GaInP/GaInAs/Ge quantum efficiency (EQE) map. The response bands of top cell, middle cell and bottom cell are 0.35-0.67 micron, 0.65-0.915 micron and 0.86-1.75 micron, respectively.

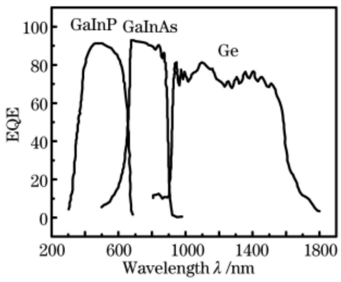

Fig.3 Spectral response of three junction GaInP/GaInAs/Ge photovoltaic cells with different junctions

The design of traditional toroidal Fresnel lens mostly uses 0.55 um as the main wavelength. Taking the traditional toroidal Fresnel lens with a radius of 90 mm and a distance of 0.3 mm as an example, the irradiance distribution on the focal plane with a radius of 5 mm is simulated by TracePro ray tracing software. When the incident light wavelength is 0.55 um and incident vertically, the simulation results are shown in Fig. 4 (a). The radiation uniformity of focal plane calculated by formula (15) is 82%, and the distribution is fairly uniform. Considering the divergence angle of sunlight and its wide spectrum, 75 equal-spaced incident light is used to simulate the sunlight in the 0.35-1.8 micron band of AM1.5D standard. The divergence half-angle is set to 0.25 mrad.

Figure 4 (b) shows that when the spectral response band of the top battery is incident, the irradiation energy mainly concentrates on the center of the focal plane. This is because the design method does not consider the focal plane distribution of different wavelengths when the broad spectral incidence occurs, which results in the low irradiation uniformity of the top battery focal plane, and the calculated irradiation uniformity is only 59%.

From Figure 4 (c) and Figure 4 (d), we can see that the focusing efficiency of the lens in the response band of the bottom battery and the middle battery is low, 60% and 54% respectively. According to the formula of 2.1 section truncation wavelength, the lower limit wavelength of 0.65 um in the response band of the bottom battery falls to the right boundary of the focal plane after refraction by the 205 ring lens, which shows that the lens area outside the 205 ring has no effect on the bottom battery. The lower limit wavelength of 0.86 um in the response band of the central cell is refracted by the 141st ring lens and falls on the right boundary of the focal plane, which shows that the lens area outside the 141st ring has no effect on the central cell.

When the whole cell responds to the incident wave band, the energy loss of the long wave part is serious, which leads to the low concentration efficiency of the bottom and middle cell responding wave bands, and the irradiation of the top cell is not uniform.

The simulation results are shown in Fig. 4 (e).

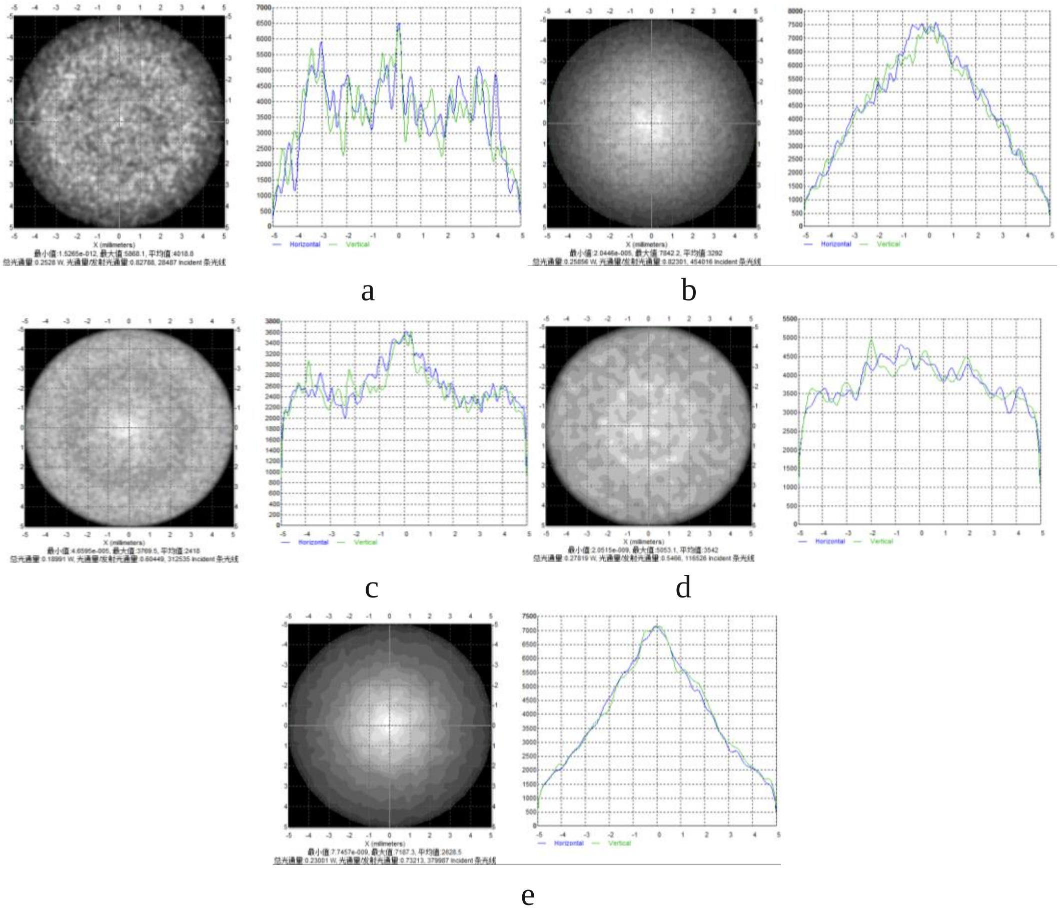

Fig. 4 the concentration distribution of the conventional torus Finel lens at different wavelengths

Processing simulation data

Tab2 traditional torus Finel lens

wavelength（μm）	0.35~ 0.67	0.65~ 0.915	0.86~ 1.75	0.38~1.8
efficiency	82%	60%	54%	73%
Evenness	59%	77%	82%	53%

3.2 Design Method

Based on the shortcomings of traditional toroidal Fresnel lens, a new design method of toroidal Fresnel lens is proposed. As shown in Fig. 5, the lens is divided into three regions: I 1, I 2 and I 3. According to the spectral response characteristics of GaInP/GaInAs/Ge multi-junction solar cells, lambda 1, lambda 2 and lambda 3 are used as the main wavelength of the design, i.e. 0.55, 0.75 and 1.25 microns. The focal planes are D1, D2 and D3 regions respectively, and d1, D2 and D3 are the focal spacing of the three regions. This design method has two main advantages: 1) The main design wavelengths of lens D1, D2 and D3 belong to the response center bands of each junction battery, respectively. It reduces the truncation loss of long wave in the outer ring of the lens, improves the focusing efficiency in the response bands of the middle and bottom batteries, and improves the uniformity of the multispectral distribution of the focal plane. 2) Optimizing each region with different focal spacing improves the spatial distribution uniformity of illumination intensity.

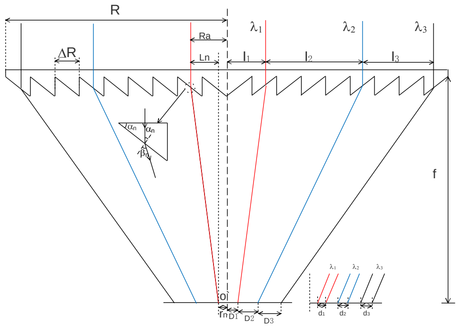

Fig.5 A new schematic diagram of a new torus Finel

According to Figure 5, there are

$$\mathrm{R}_n = \Delta R \times (n-1) + \frac{1}{2}\Delta R \tag{18}$$

$$L_n = R_n - r_n \tag{19}$$

$$n_i = a + b\lambda_i^{2} + c\lambda_i^{-2} + d\lambda_i^{-4} + e\lambda_i^{-6} + f\lambda_i^{-8},\ i = 1,2,3 \tag{20}$$

$$r_n = n \times d_1, \lambda_1 = 0.55\mu m; 0 < n \le I_1 \tag{21}$$

$$r_n = D_1 + (n - I_1) \times d_2, \lambda_2 = 0.75\mu m; I_1 < n \le I_2 \tag{22}$$

$$r_n = D_1 + D_2 + (n - I_1 - I_2) \times d_3, \lambda_2 = 1.25\mu m; I_2 < n \le I_3 \tag{23}$$

$$\partial_n = \arctan\left(\frac{\sin(\arctan(L_n / f))}{n_i - \cos(\arctan(L_n / f))}\right) \tag{24}$$

In the formula, n I is the refractive index of the lens material corresponding to lambda i, Rn is the distance between the center point of the nth ring sawtooth and the central axis, and RN is the distance between the focal spot position of the nth ring sawtooth and the central axis. From this, the height angle alpha n of the saw teeth of each ring lens can be calculated.

4. Modeling and Simulation of new toroidal Fresnel lens

4.1 Lens Parameter Setting and Modeling

The design of the lens involves six variables and has constraints. In order to obtain the optimal solution, the mixed penalty function method based on particle swarm optimization is used to solve the parameters.

The optimum parameters are calculated by using MATLAB. Lens size: R = 90 mm, ring tooth width: R = 0.3 mm, focal length: f = 180 mm, focal plane area: D1 = 1.05 mm, D2 = 3.3 mm, D3 = 0.296 mm, focus interval D1 = 0.025 mm, D2 = 0.03 mm, D3 = 0.002 mm. The concentration ratio is 366 times.

According to the parameters obtained, the model is established by SolidWorks as shown in Figure 6.

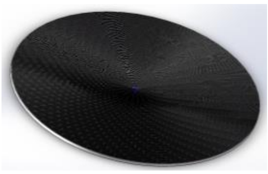

Fig. 6 simulation model of a new toroidal Finel lens

4.2 Optical simulation

In order to verify the above design method, TracePro is used for ray tracing. Under the incident conditions of 0.35-0.67, 0.65-0.915, 0.86-1.75 and 0.38-1.8 microns, the new toroidal Fresnel lens is simulated and its irradiance distribution on the focal plane with radius of 5 mm is analyzed. The simulation results are shown in Figure 7.

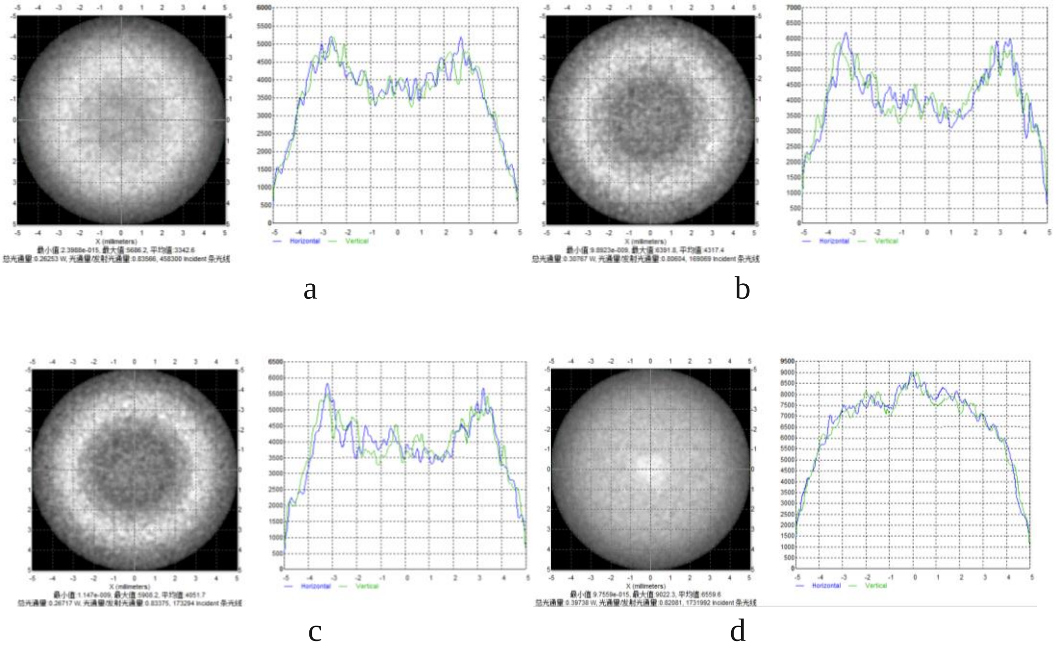

Fig. 8 the concentration distribution of the new toroidal Finel lens at different wavelengths

Processing simulation data

Tab3 a new type of torus Finel lens

wavelength（μm）	0.35~ 0.67	0.65~ 0.915	0.86~ 1.75	0.38~1.8
efficiency	83%	80%	83%	82%
Evenness	74%	81%	81%	80%

As shown in Table 3, the new toroidal Fresnel lens has a high concentration efficiency and radiation uniformity in the whole spectrum and the response bands of the junction photovoltaic cells. The uniformity of focal plane irradiation is more than 74%, the focusing efficiency is more than 80%, and the geometric focusing ratio is 366 times, which achieves the optimization goal.

5. Conclusion

The third generation photovoltaic system has broad prospects for development. The power generation efficiency of the whole system is affected by irradiation uniformity and concentration efficiency.

In this paper, by establishing a mathematical model, using the design method of multi-principal wavelength and variable focus interval, the improved hybrid particle swarm optimization algorithm is used to select the optimal design parameters. The simulation results show that the new toroidal Fresnel lens can concentrate light uniformly and efficiently on all junction photovoltaic cells. The concentrating efficiency is more than 80%, the irradiation uniformity is more than 74%, and the geometrical concentrating ratio is 366 times. Compared with the traditional toroidal Fresnel lens, the optical performance has been significantly improved, the design goal has been achieved, and the correctness of the design method has been verified.

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