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High concentration and homogenized Fresnel lens without secondary optics element

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A B S T R A C T

In this paper, we design a single concentrator to homogenize and concentrate the solar energy. The proposed concentrator only consisted of an array of refraction prisms. In order to homogenize the irradiance, all pitches of the Fresnel concentrator focus on the different position of the receiver. Finally, the Fresnel lens that achieves the uniformity of U is 14.6. An acceptance angle of 0.305° is achieved without using additional secondary optics. Full Width at Half Maximum (FWHM) of illumination distribution is 1.4 mm.

1. Introduction

Currently, the III–V based solar cell with conversion efficiency 41.6% in 2009[1] and conversion efficiency 42.3% in 2010 [2]is the best one among the solar cell materials. However, the cost of the III–V based solar cell is also the most expensive one compared to the other solar cells materials [3]. In order to reduce the cost of III–V solar cell, a concentrator needs to keep the same power generation within a reduced solar cell area. Thus the concentrator becomes a key component integrated with high cost solar cell module to fabricate a high concentration photo voltaic (HCPV) system.

The Fresnel lens is a famous optical element as a concentrator because the Fresnel lens concentrator has various advantages such as a compact size, the lower weight and the material cost saving etc. The types of Fresnel concentrator were divided into two main types: the first is a refractive type [4], and the second is a hybrid type [5]. The goal of the concentrator is to increase the concentrator ratio and maintains the accept angle at high level simultaneously. However, the concentrator also generates hot spots at the solar cell surface. The hot spots degrade the reliability and the conversion efficiency of the solar cell module [6,7]. In order to reduce the damage resulted from hot spots and increase the accept angle, the two main types of Fresnel concentrators must integrate a second optical element (SOE) to improve the acceptant angle and homogenize the energy distribution simultaneously [8,9]. The secondary optical element will increase the solar cell module cost and reduce the available photon quantity due to the Fresnel loss. Thus, designing a high concentration and homogenized Fresnel lens without SOE is an important issue in III–V solar cell industry.

In this paper, we propose an idea for the development of high concentration and homogenized Fresnel lens without SOE. The

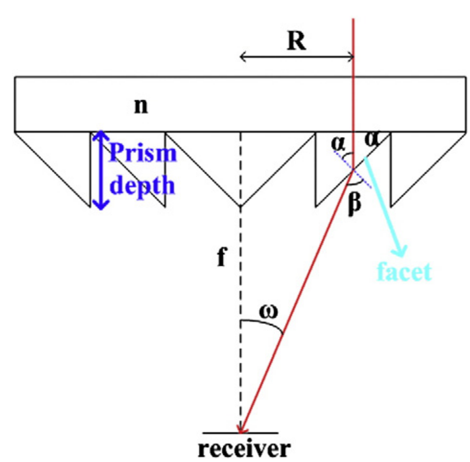

Fig. 1. Schematic of planar Fresnel lens.

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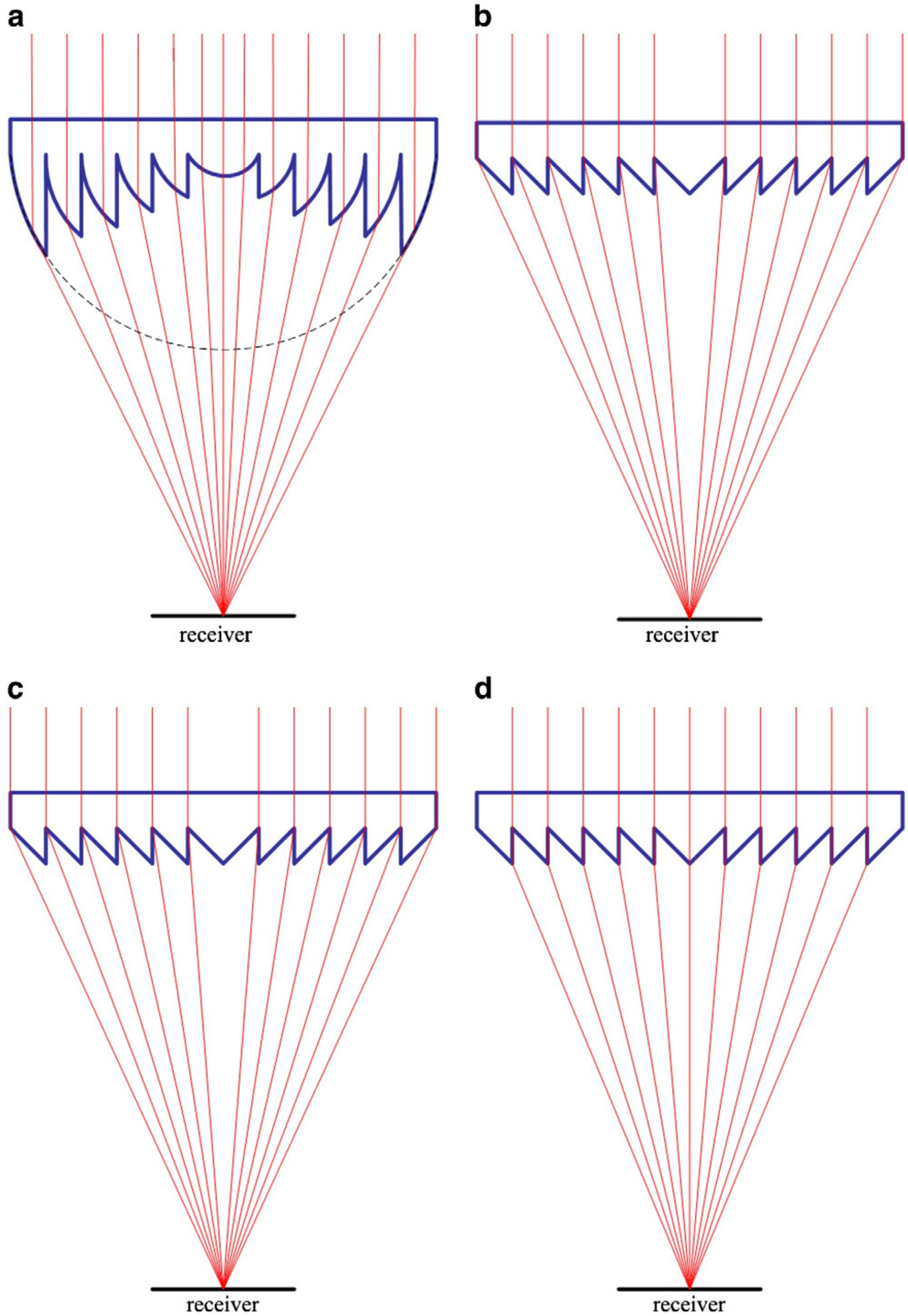

Fig. 2. The different type focus on the center of the receiver (a) Conventional type: The plano-convex lens. (b) First type: The right ray focus on the center of the receiver. (c) Second type: The center ray focus on the center of the receiver. (d) Third type: The center ray focus on the center of the receiver.

proposed Fresnel lens has several advantages such as no total internal reflection (TIR) zone, shallow depth, and easy to manufacture. High concentration ratio and uniformity are two important parameters during the design of Fresnel lens applied to solar cell module. Because high concentration ratio can reduce cost and high uniformity can increase conversion efficiency in the III–V material solar cell. The optical performances of the designed Fresnel lens are simulated by using the nonsequential ray tracing software, Light Tools [10]. An optimized structure is designed by modulating the geometric parameters of the Fresnel lens. The concentration ratio is 1018×, acceptance angle of θ is 0.305°, F-number is 1, and uniformity of U is 14.6 in the optimized Fresnel lens design.

2. The mathematical equation and the parameters for simple Fresnel lenses

A simple Fresnel lens is sketched in Fig. 1. The Fresnel lens consists of serial pitches of Fresnel lens facets. The Four equations can describe each pitch of the Fresnel lens [11].

$$n\sin\alpha = \sin\beta \tag{1}$$

$$tan\omega = \frac{R}{f} \tag{2}$$

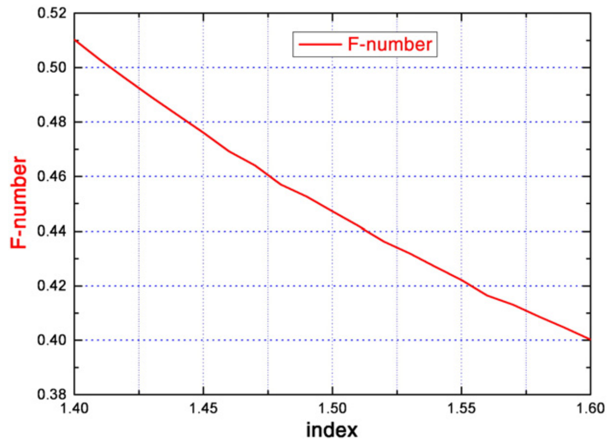

Fig. 3. The relation between index and f-number.

$$\beta = \alpha + \omega \tag{3}$$

$$tan\alpha = \frac{R}{n\sqrt{R^2 + f^2 - f}.} \tag{4}$$

The incident ray follows Snell's law. As shown in Fig. 1, n is the refractive index of the Fresnel lens, f is the focal length, R is the distance between incident ray and the center axis of the Fresnel lens, ω is an angle between the normal of the receiver and the refractive ray, α is an angle between the normal of the Fresnel lens's facet and the incident ray, β is an angle between the normal direction of the Fresnel lens's facet and the refractive ray. In this Fresnel lens, the material is polymethyl methacrylate (PMMA), which is a typical optical plastic with a refractive index from 1.48 to 1.5 for a wavelength from 1600 to 400 nm [12].

For the concentrator design, the uniformity is a key performance for Fresnel lens design. Owing to the high concentration ratio, energy distribution always has a hot spot. This result will cause much difficulty to evaluate the uniformity by the traditional way. In order to

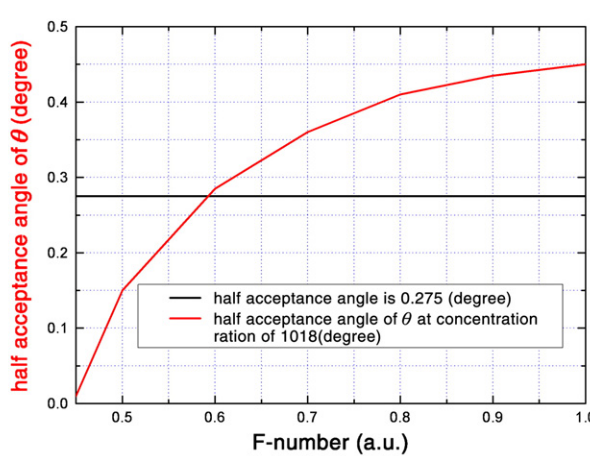

Fig. 4. The relation between F-number and acceptance angle of θ at concentration ratio of 1018×.

Table 1
The simulation result in different types of Fresnel lens.

	Conventional type	First type	Second type	Third type
Uniformity	0.148	0.319	0.152	0.387
Half acceptance angle (degree)	0.45	0.21	0.45	0.19
Prism depth (mm) at the diameter of F/# 1	~3.17	~0.27	~0.27	~0.27

evaluate the degree of uniformity, a parameter of the uniformity is defined:

$$Uniformity\ \ of\ \ U = \frac{C}{\sum\left(I_{n,m} - I_{avg}\right)^2}, n, m = number\ \ of\ mesh, C = 10^{18}. \tag{5}$$

The receiver is divided into n by m meshes. Here, $I_{n,m}$ is the intensity of the each mesh at the receiver. I_{ave} is the average intensity in all meshes, and C is a constant. A suitable value of the C is selected in this Fresnel lens design. The acceptance angle of θ is defined as the incidence angle at which the concentrator collects 90% of the solar power. The concentration ratio is defined as the concentrator aperture area divided by receiver area. F-number (F/#) is defined as the focal length divided by the concentrator diameter.

3. Optic design and simulation

3.1. High concentration

The traditional Fresnel lens is shown in Fig. 2(a)[11]. There is a serious spherical aberration in the plano-convex lens under low F/# condition. Therefore, the control of the focusing situation is challenged. Thus, higher order aspheric coefficients are applied to reduce spherical aberration. However, the higher order aspheric coefficient would introduce a deeper prism depth. In order to obtain high concentration with a high accept angle, we use the Eq. (4) to design three types for the Fresnel lens. The first type of Fresnel lens uses the right edge ray of the each pitch to passes through the facet, then focus on the center of the receiver as shown in Fig. 2(b). The second type of Fresnel lens uses the center ray of the pitch to pass through the facet, then focus on the center of the receiver as shown in Fig. 2(c). The third type of Fresnel lens uses the left edge ray of each pitch to pass through the facet, then focus on the center of the receiver as shown in Fig. 2(d).

Under a low F/# and a high concentration ratio, the angle α of the edge pitch at the Fresnel lens would get larger. When the angle α is larger than the total internal angle, the total internal reflection happens. This phenomenon is not our design condition. For n = 1.5, the total internal reflection happens as α > 41.81°. According to the mathematical equations, the corresponding ω is 65.77°which implies that the F/# is limited to be 0.45. Moreover, the depth of pitch also will increase the difficulty to do the manufacture process for the Fresnel lens. For production issue, the angle α is chosen for the refractive condition. According to Eq. 4, one can arrange this equation to get the relationship between the index and F/# of the Fresnel lens under refractive condition. The Eq. 6 shows this relationship which is shown in Fig. 3 as well. It can be seen that the index increase with the F/# of Fresnel lens decreasing. Owing the index of PMMA is 1.493, we can use the F/# of 0.45 as our design target.

$$sin^{-1}\left(\frac{1}{n}\right) = tan^{-1}\left(\frac{1}{n\sqrt{1^2 + 4(F/\#)^2} - 2(F/\#).}\right) \tag{6}$$

The relation between F/# and acceptance angle is simulated under the concentration ratio of 1018× .The result is shown in Fig. 4. It is

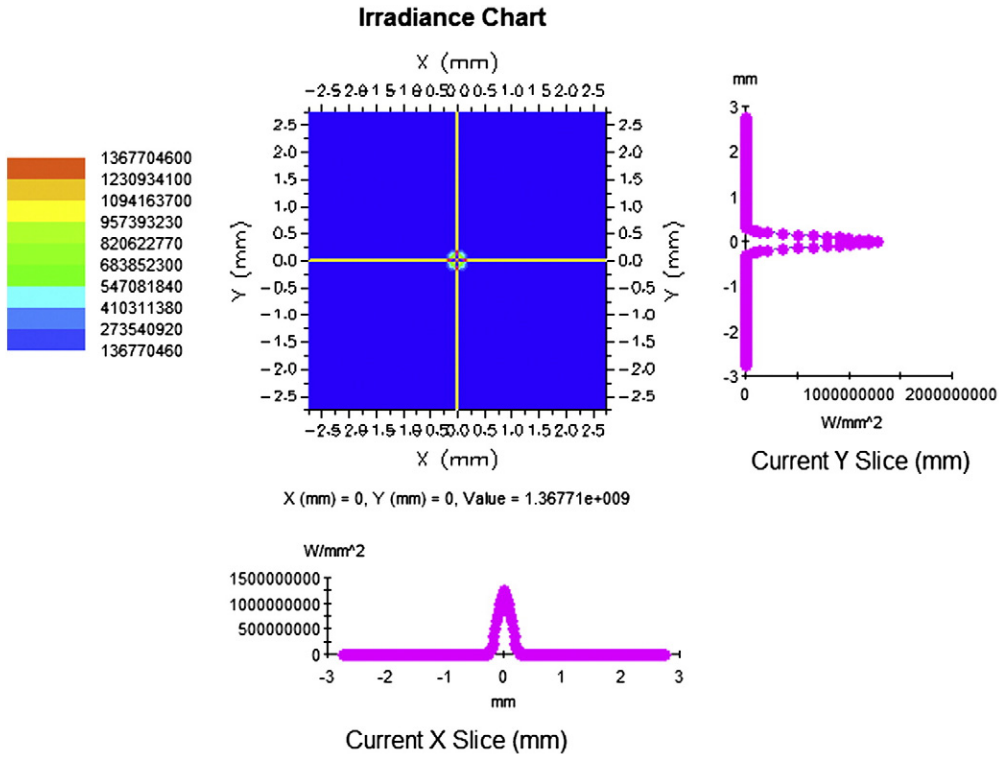

Fig. 5. The energy distribution of the sencond type Fresnel lens.

shown that the acceptance angle decreases with the F/# of Fresnel lens increasing. The acceptance angle of θ is 0.01 at F/# of 0.45. The acceptance angle of θ must be larger than the solar angle of 0.275°. Moreover, considering the manufacturing tolerance [13], the F/# of 1 is chosen as our designed specification.

For the HCPV industry, the concentration ratio of the Fresnel lens is around 500–800. In our design specification, the concentration ratio is 1018×, focal length is 198 mm, the pitch size is 0.3 mm, and F-number is 1. The receiver size is 5.5 mm × 5.5 mm. In order to evaluate our design, the optical performances are analyzed by using the software, Light Tools. Before homogenizing the distribution of the irradiance, the four types of the Fresnel lens are designed and simulated. The simulation result is shown in Table 1. The acceptance angle is important in the Fresnel lens. The acceptance angle of θ must be larger than the solar angle of 0.275° for the concentration application. Because the acceptance angle of the second type is higher than other two types and the prism depth of the second type is lower than conventional type. The prism depth is too deep to manufacture. Thus, the second type is chosen as our design way to add the homogenization function with our concentrator.

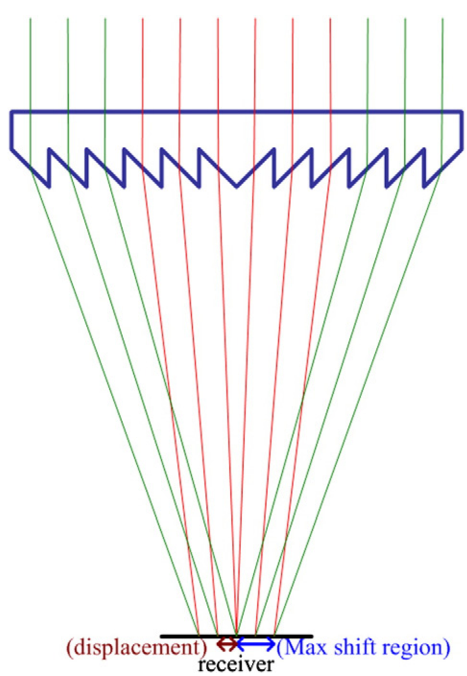

Fig. 6. An idea homogenizes the irradiance on the receiver like solar cell.

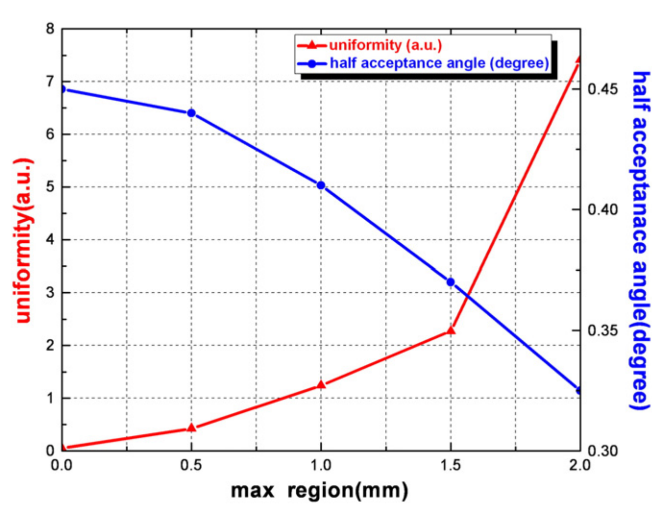

Fig. 7. The relation between max region, acceptance angle of θ, and uniformity.

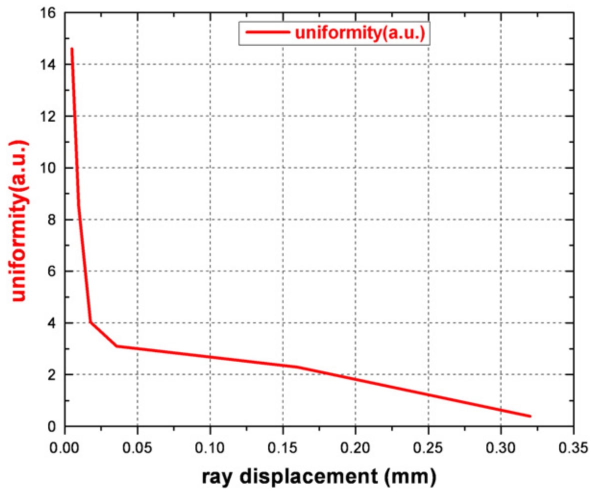

Fig. 8. The relation between uniformity and displacement.

Fig.10. Sample for Fresnel lens.

The simulation result of the second type focusing on receiver is over concentrated, and it is non-uniform as shown in Fig. 5. The FWHM of illumination distribution is 0.04 mm. The energy is too concentrated to get a hot spot. This energy hot spot will produce the high temperature. The phenomenon not only causes the injury to the solar cell, but also reduces the efficiency of generating electricity.

3.2. Homogenization

Moreover, an idea of focusing on the receiver uniformly is proposed as shown in Fig. 6. The incident ray on the right pitch will focus on the right of the receiver uniformly. The max region of D is the distance from center of the receiver to the max focusing position. The ray displacement of d is the distance from the focusing position of the incident ray on each adjacent pitch.

The design method of the second type is achieved by changing the slope of each pitch to reach homogenized. First step, we observe the relation between max region of D, acceptance angle of θ, and uniformity of U. The simulation result is shown in Fig. 7. When the max region of D is increased to improve the uniformity, the acceptance angle will get smaller. To achieve the trade-off conditions, the relation of uniformity and the acceptance angle is considered, and then the point of intersection is chosen as shown in Fig. 7. The max region of D is 1.6 mm, uniformity of U is 3.023, and acceptance angle of θ is 0.365° at this point.

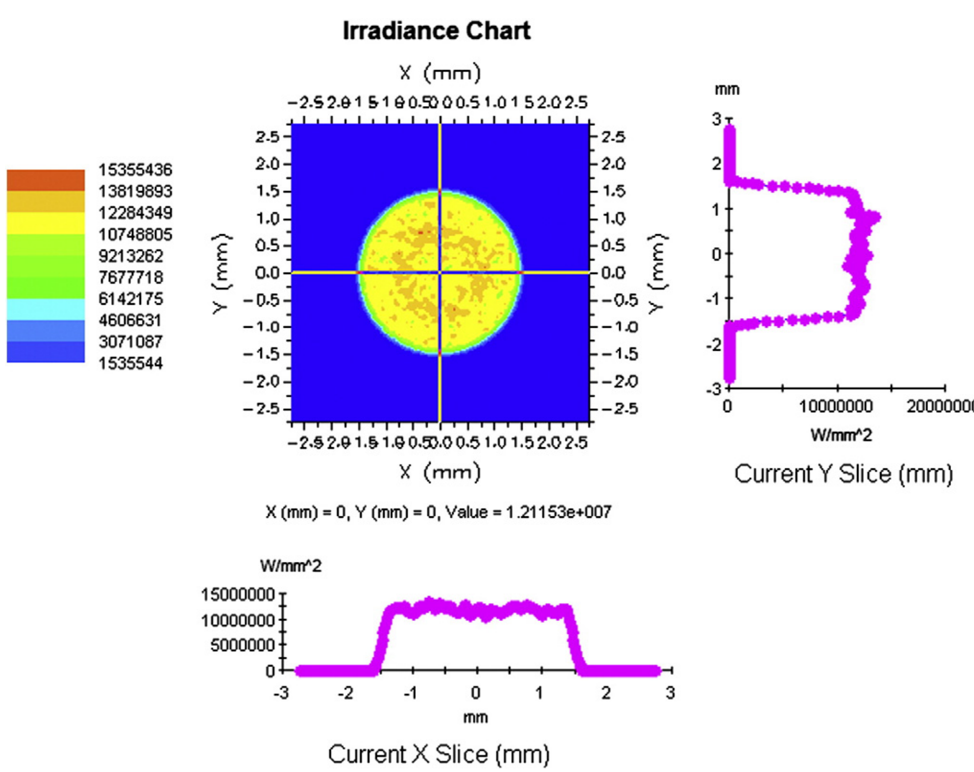

Fig. 9. The energy distribution is uniform in the best design.

Table 2
Specification comparisons between reference [9] and our best design.

	Reference [14]	FLATCON modules [15]	The optimized design in this paper
Concentration ratio	314	500	1018
Design type	Hybrid (refractive zone and TIR zone)	Refractive (refractive zone only)	Refractive (refractive zone only)
F-number (F/#)	0.5	1.677	1
Focal length (mm)	60	75	198
Uniformity	Non-uniform	Non-uniform	Uniform(14.6)
Half acceptance angle (degree)	0.78	0.6	0.305

At second step, the max region of D is fixed and the ray displacement of d for each pitch is adjusted. The different pitches may focus incident ray on the receiver in max region of D under different ray displacement of d. The simulation result is shown in Fig. 8. The uniformity decreases as ray displacement of d increases. Therefore, a max uniformity at all pitches focus on different position can be obtained. The max uniformity of U is 14.6. Moreover, the acceptance angle decreases from 0.365° to 0.305° due to the uniformity increase from 3.023 to 14.6.

The optimized energy distribution under the max uniformity is shown in Fig. 9. The FWHM of illumination distribution is 1.4 mm. The uniformity degree is significantly improved after homogenizing. The results from the non-uniform distribution and the uniform distribution are shown in Fig. 5 and Fig. 9, respectively. The FWHM of illumination distribution increases from 0.04 mm to 1.4 mm. Thus, the idea can homogenize the uniformity and increases the FWHM of illumination distribution on the receiver.

3.3. Fabrication and comparison

According to the design rule of high concentration homogenized Fresnel lens, we have done some tooling to manufacture the Fresnel lens. The sample is shown in Fig.10. Comparing our design specification to the other Fresnel lens designs [14,15], the result is shown in Table 2. We can obtain higher concentration ratio and uniformity than the other designs. In our design, there is only a refractive zone without TIR zone. The TIR zone has two main disadvantages. The incident rays leaving the facet are often blocked by the tip of next pitch under the TIR zone [16]. The refractive type of the Fresnel lens is easier to manufacture than the hybrid type of the Fresnel lens, because the prism depth of the refractive type is shallower than it in the hybrid type. As a result, the optimized designing Fresnel lens can reduce cost and increase conversion efficiency in the III–V material solar cell.

4. Conclusion

In this paper, the design can increase the uniformity a lot and keep the acceptance angle within solar angle without SOE and complicated theoretical approaches. In order to homogenize the irradiance, the different pitches should focus on the different position of the receiver, and the uniformity can be improved. A versatile idea is proposed to determine the better geometry of Fresnel lens that yields not only uniform concentration but also a high concentration ratio. The uniformity of U is 14.6 and the concentration ratio is 1018 without additional secondary optics element. Moreover, the acceptance angle of θ can keep at 0.305° under the same Fresnel lens condition.

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