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Research Paper

Design and optical analysis of the band-focus Fresnel lens solar concentrator

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HIGHLIGHTS

- A new kind of band-focus Fresnel lens solar concentrator was proposed.
- The design principle of band-focus Fresnel lens concentrator was given.
- Optical analysis of this Fresnel lens concentrator showed a good concentrating uniformity.

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ABSTRACT

Solar energy is one of the most promising renewable energies and meaningful for the sustainable development of energy source. In this paper, a new kind of band-focus Fresnel lens solar concentrator was proposed. The design principle of this solar concentrator was given and the spectral concentrating performance was simulated by the means of Monte Carlo Ray Tracing Method (MCRT), which was compared with the linear Fresnel lens. The results show that both the spectral concentrating uniformity and optical efficiency of the band-focus Fresnel lens were better than those of the linear one. Meanwhile several characteristic parameters of the band-focus Fresnel lens concentrator were analyzed under different conditions and it can be drawn from the results that a high-ratio band-focus Fresnel lens concentrator could increase the optical efficiency of a concentrating photovoltaic (CPV) system.

1. Introduction

Solar energy is one of the most promising renewable energies and meaningful for the sustainable development of energy source. As the solar radiation energy flux density is low on the surface of the earth, the spectral concentrating can be used in the solar energy photovoltaic utilization process to reduce costs. Fresnel lens is a common kind of spectral concentrator, which is used not only in PV systems [1–3] but also in solar thermal systems [4–6]. Traditional Fresnel lenses make lights focus to a point or a line with wedges which are distributed on a plane or a curved surface [7,8]. When they are used in PV systems, the energy flux densities on solar cells are very non-uniform and that reduces the efficiency of solar modules [9,10].

For this problem, Ryu et al. improved the point-focus Fresnel lens and made rays through the new lens focus to a square which had the same size as a solar cell [11]. That improves the spectral uniformity, but because of the design limitations, this new lens must face the incident rays strictly when it is used in PV systems. Otherwise, even a very small deviation could make the concentrating light deviate from solar cells and decrease the total efficiency greatly. So a precise two-axis sun-tracker is necessary for this kind of Fresnel lens.

This paper proposes a new kind of Fresnel lens concentrator, based on the linear Fresnel lens, which could focus incident rays to a uniform solar flux band. The optical simulation and analysis of the band-focus Fresnel lens were carried out by the means of Monte Carlo Ray Tracing Method, aiming at the investigation of the spectral concentrating performance of this new concentrator.

2. Concentrator design

In order to make incident rays focus to a band which is presented in Figs. 1 and 2, the design principle was given as follows: (1) The horizontal length of the Fresnel lens d was set to be odd times of the width of a solar cell w, and the ratio N was equal to d/w. The horizontal length was divided to N units. (2) In these N

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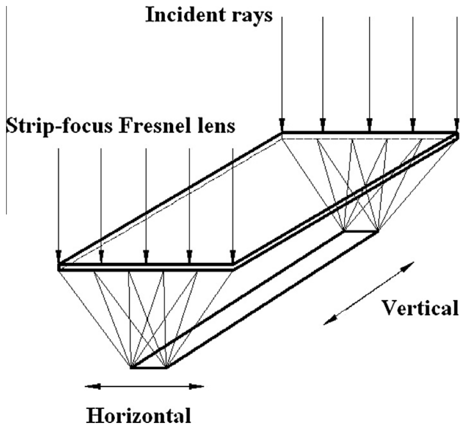

Fig. 1. Spectral concentration effect of band-focus Fresnel lens.

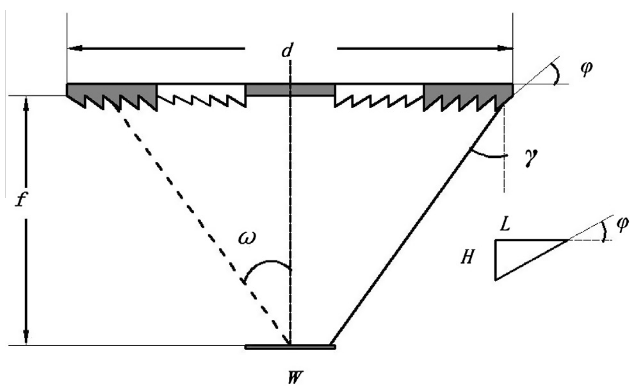

Fig. 2. Design of the horizontal orientation of band-focus Fresnel lens.

units, the center one was made as a plane without wedges. Other units all have the same number of wedges and the angles φ of every wedge which were in the same unit should be the same.

If the index of refraction of the lens material was n, the angle φ of a wedge could be calculated as following:

$$\varphi = \arctan\left(\frac{\sin\gamma}{n - \cos\gamma}\right) \tag{1}$$

where γ was the light deviation angle of this wedge, which can be seen in Fig. 2. When the wedge angles of the Fresnel lens were given, the overall size of the lens would be obtained according to the size of solar cells and the focal length f. In this paper, the size of solar cells was assumed to be 25 mm × 125 mm, f would be changed according to different conditions.

The ideal optical efficiency was an important characteristics parameter of the band-focus Fresnel lens. When the light was normal incident, the energy flux transmission efficiency should be [12]:

$$\tau_1 = \frac{4n}{(n+1)^2} \tag{2}$$

As shown in Eq. (2), the energy flux transmission efficiency was only related to the index of refraction of lens material when the light was normal incident.

The energy flux transmission efficiency of the light output surface of the band-focus Fresnel lens was equal to the weighted average of the energy flux transmission efficiencies of all wedges and the center plane [12]:

$$\tau_2 = \left(\sum_{1}^{M}\tau_j l_j + w\tau_1\right)\Big/ d \tag{3}$$

where τ_j and l_j were the energy flux transmission efficiency and tooth width of Wedge j, respectively. The ideal optical efficiency of the lens was expressed as following:

$$\eta = \tau_1\tau_2 \tag{4}$$

The optical efficiency of lens under the condition which the rays were not normal incident was analyzed later in this paper.

3. Method and calculation model

Monte Carlo Ray Tracing Method (MCRT) was employed for the spectral concentrating simulation of the band-focus solar concentrator. It was a statistical method of tracking the random process of a large number of beams. The calculation process of MCRT was: Assuming that solar radiation energy was carried by a lot of beams evenly, every beam would experience many optical processes including reflection, refraction, absorption and scattering. Whether these optical processes occurred or not were controlled by random numbers. By tracking the propagation processes of these beams, the energy flux density distribution on the radiation absorbing surface could be obtained [13].

Assuming that incident rays distributed evenly on the incident plane of the band-focus Fresnel lens and this plane was considered as the emitting surface of sampling beams, the probability model of the emitting point (x_0, y_0, z_0) was:

$$\begin{cases} x_0 = x_L \times R_X - x_L/2 \\ y_0 = f \\ z_0 = z_L \times R_Z \end{cases} \tag{5}$$

where $R_X,\ R_Z \in (0,1)$ were the random numbers of x axis and y axis respectively, and x_L, z_L and f were the x axis length, y axis length and focal length of the band-focus Fresnel lens respectively. The non-parallel angle of solar radiation was 32′, so the incident rays was considered as a light cone with $\theta_a = 16'$. In this cone, the solar energy distribution followed the Lambert law which was that the directional radiation intensities were the same. So we could obtain the zenith angle and circumferential angle perpendicular to the incident light direction as follows [14]:

$$\theta = \arcsin\sqrt{R_\theta \times \sin(\theta_a^2)} \tag{6}$$

$$\varphi = 2\pi R_\varphi \tag{7}$$

where $R_\theta,\ R_\varphi \in (0,1)$ were the random numbers of cone angle and circumference along the emitting direction. The direction vector of the normal incident light $\boldsymbol{P}$ was:

$$\boldsymbol{P} = (\sin\theta\sin\varphi, -\cos\theta, \sin\theta\cos\varphi) \tag{8}$$

and the direction vector of the refraction light $\boldsymbol{A}$ was:

$$\boldsymbol{A} = \boldsymbol{P} + C\boldsymbol{N} \tag{9}$$

where $\boldsymbol{N}$ was the normal direction vector on the incident point of the refraction surface, and C was a constant. If the incident angle was α, the refraction angle was β, C would be:

$$C = n\cos\beta - \cos\alpha \tag{10}$$

When the rays were not normal incident, the direction vector $\boldsymbol{P}^*$ could be obtained by using a transformation matrix U:

$$\boldsymbol{P}^* = U\boldsymbol{P} \tag{11}$$

where transformation matrix was:

$$U = \begin{bmatrix} u_{11} & u_{12} & u_{13} \\ u_{21} & u_{22} & u_{23} \\ u_{31} & u_{32} & u_{33} \end{bmatrix} \tag{12}$$