Optics & Laser Technology 60 (2014) 27–33

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Optimization design of hybrid Fresnel-based concentrator for generating uniformity irradiance with the broad solar spectrum

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ARTICLE INFO

Article history:
Received 15 September 2013
Received in revised form
10 December 2013
Accepted 27 December 2013
Available online 24 January 2014

Keywords:
Optical design
Fresnel-based lens
Photovoltaic concentrator

ABSTRACT

This paper presents a novel hybrid Fresnel-based concentrator with improved uniformity irradiance distribution on the solar cell without using secondary optical element (SOE) in the concentrator photovoltaic (CPV) system to overcome the Fresnel loss and to increase the solar cell conversion efficiency. The designed hybrid Fresnel-based concentrator is composed of two parts, the inner part and the outer part. The inner part is the conventional Fresnel lens, while the outer part is double total internal reflection (DTIR) lens. According to the simple geometrical relation, the profile of the proposed hybrid Fresnel-based concentrator is calculated as an initial design profile. To obtain good irradiance uniformity on the solar cell, optimal prism displacements are optimized by using a simplex algorithm for collimated incident sunlight based on different prism focus on different position principles. In addition, a Monte-Carlo ray-tracing simulation approach is utilized to verify the optical performance for the hybrid Fresnel-based concentrator. Results indicate that the hybrid Fresnel-based concentrator designed using this method can achieve spatial non-uniformity less than 16.2%, *f*-number less than 0.59 (focal length to entry aperture diameter ratio), geometrical concentrator ratio 1759.8 ×, and acceptance angle $\pm 0.23^{\circ}$. Compared to the conventional Fresnel-based lens and the traditional hybrid Fresnel-based lens, the optimized concentrator yields a significant improvement in irradiance uniformity on the solar cell with a wide solar spectrum range. It also has good tolerance to the incident sunlight.

1. Introduction

High uniformity irradiance on the solar cell is desirable for the photovoltaic (PV) system to increase the conversion efficiency of III–V compound multi-junction (MJ) solar cells. However, the homogenization of the irradiance distribution in the conventional Fresnel-based concentrated photovoltaic (CPV) concentrator with a series of refractive prisms [1,2], is realized by adding a secondary optical element (SOE) between primary optical element (POE) and solar cell.

Recently, several approaches have been developed to improve the irradiance distribution, including freeform lens, hemispherical glass dome, dielectric total internal reflection concentrators (DTIRC), and Fresnel Köhler concentrator [3–5]. The optical performance is summarized in reference [3]. Among these approaches, with respect to other non-imaging concentrators, the Fresnel Köhler concentrator is a reliable and robust performance concentrator. Since Fresnel loss, such as absorption loss and reflection loss, is inevitable, a double total internal reflection (DTIR) prism was used to design the Fresnel-type concentrator to overcome efficiency loss [6]. However, this type of concentrator also generates hot spots on the solar cell, and the absorption loss may increase when the SOE is used. Ryu et al. [7] proposed a modularly faceted Fresnel lens for obtaining irradiance on the solar cell without using SOE, aiming at improving the conversion efficiency of the solar cell. Later, Pan et al. [8] proposed an array of conventional refraction prisms for improving the solar cell uniformity as well as the acceptance angle. However, they do not take the effect of the solar spectrum on the solar cell into consideration. To increase the concentration ratio (CR), one of the methods is to expand the aperture of the concentrator. Nevertheless, the more far away from the center of Fresnel lens, the more serious the Fresnel loss appeared [9,10]. Combining the traditional Fresnel-based concentrator, Wallhead et al. [9] introduced a hybrid Fresnel-based concentrator to overcome the Fresnel loss which causes an increase in Fresnel diameter and generation of focal point on the solar cell; this characteristic makes it possible to decrease the conversion efficiency of III–V compound MJ solar cells. The Languy group developed the shaped achromatic Fresnel lenses [11], which can be used to enhance the concentration ratio and to achieve a spectrally uniform flux on the solar cell, but two prisms are separated by a very small air gap that will limit its possibility for mass production.

Using the Pan method, this paper presents an optimized hybrid Fresnel-based photovoltaic concentrator with high concentration and improved uniformity on the solar cell without using SOE.

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http://dx.doi.org/10.1016/j.optlastec.2013.12.021

The proposed hybrid Fresnel-based concentrator consists of conventional prisms and DTIR prisms in the inner and outer areas, respectively. This will lead to significantly reduced Fresnel loss and achieved high CR. The hybrid Fresnel-based concentrator is firstly calculated according to a simple geometric relation. After that, the segment method [12,13] is used to establish the Fresnel-based concentrator profile from a string of discrete points. Finally, based on the revised simplex algorithm, a focus displacement approach is used to optimize the uniformity of the solar cell. The designed Fresnel-based concentrator demonstrates that this method can meet the requirements of both uniformity and good acceptance angle on the solar cell, therefore, helps to increase the conversion efficiency of III–V compound MJ solar cells.

The rest of the paper is organized as follows: the problem using conventional prism, single TIR (STIR) prism, and DTIR prism in the CPV system is compared and analyzed in Section 2. At the same time, chromatic dispersion is analyzed. In Section 3, we also describe the method of designing the initial hybrid Fresnel-based concentrator, the optimization method respectively. The optical performance of the optimized system is analyzed in Section 4. Finally, the conclusions are drawn in Section 5.

2. Statement of the problem

2.1. Optical transmission

Three types of pitches are shown in Fig. 1. Fig. 1(a) shows the conventional prism, the incident ray is refracted by the hypotenuse. Fig. 1(b) shows the STIR prism, the incident ray is reflected by the hypotenuse, then refracted by the leg. As shown in Fig. 1(c), the incident ray will be reflected twice in the prism, and then deflects to the prescribed position while emitting from the hypotenuse, which is called DTIR prism. According to the geometric relation, the relation between the prism angle θ and the collection angle ω for the conventional prism, STIR prism and DTIR prism can be calculated as follows, respectively [14]:

$$n\ \sin(\theta) = \ \sin(\theta+\omega) \tag{1}$$

$$n\ \sin(2\theta-90^{\circ}) = \ \sin(90^{\circ}-\omega) \tag{2}$$

$$n\ \sin(3\theta-180^{\circ}) = \ \sin(\theta-\omega) \tag{3}$$

where n is the refractive index of the material.

It is well known that Fresnel loss appears when light travels from one medium into the other and it's optical transmission can be expressed according to the Fresnel equation [15]:

$$T = 1-\frac{1}{2}\left[\frac{\sin^2(\alpha-\beta)}{\sin^2(\alpha+\beta)}+\frac{\tan^2(\alpha-\beta)}{\tan^2(\alpha+\beta)}\right] \tag{4}$$

where α is an angle between the normal of the prism surface and the incident ray, and β is an angle between the normal direction of the prism surface and the refractive ray.

Substituting Eqs. (1)–(3) into Eq. (4), the relationship between optical transmission and collection half angle of conventional prism and two TIR prisms is calculated, as shown in Fig. 2, and the prism material is polymethyl methacrylate (PMMA, n=1.49), which is an excellent material used in the fabrication of the Fresnel-based concentrator. It is shown that the optical transmission of conventional prism decreases rapidly when collection half angle is greater than about 20°, while an increasing collection half angle leads to an increasing optical transmission of STIR. However, optical transmission of DTIR changes slowly with an increasing collection half angle.

2.2. Chromatic dispersion

Chromatic dispersion is another important factor causing ununiformity of the acceptor when imaging with a Fresnel-based concentrator. Since the refractive index of a material depends on the wavelength of illumination. The simplest analytical expression,

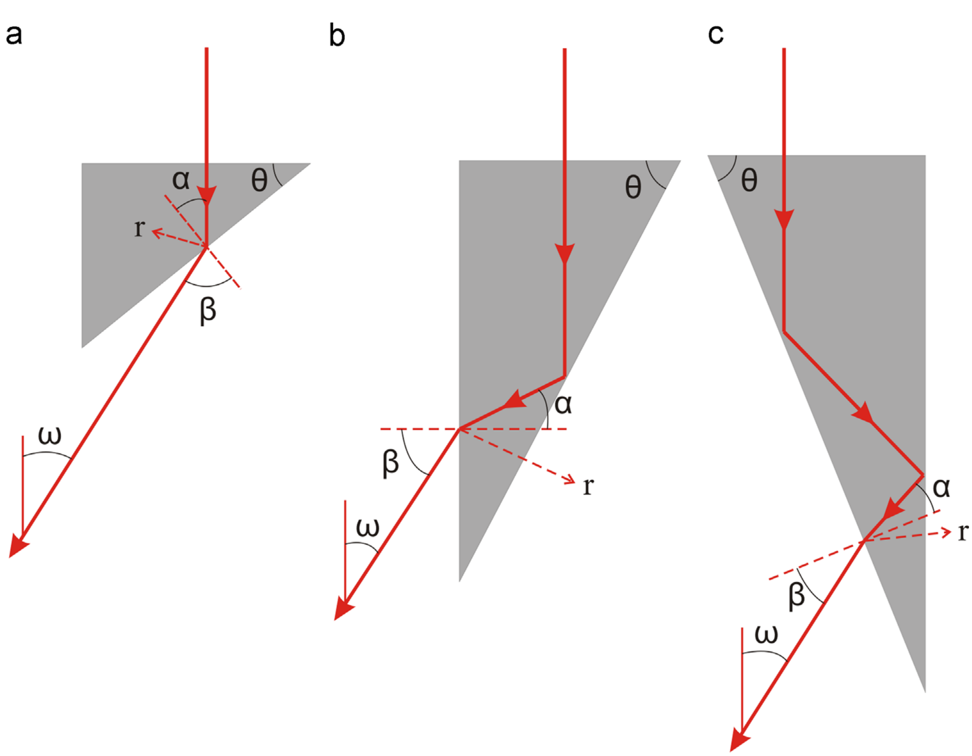

Fig. 1. The different types of pitches deflect light to the prescribed position of the solar cell (a) conventional prism, (b) STIR prism, and (c) DTIR prism.