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Design and preliminary experiments of truncated ball lens as secondary optical element for CPV system

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ABSTRACT

The Concentrated Photovoltaic (CPV) technology based on the use of high-efficiency multi-junction solar cells has higher power generation efficiency than other photovoltaic power generating technology. However, the cost and reliability of CPV technology are the primary reasons that restrict its progress. A truncated ball lens as a secondary optical element for CPV optical system is proposed in this paper to reduce the cost and improve the reliability. Theoretical analysis and experimental investigations were conducted on a concentrator with geometrical concentration ratio of 625×, a flat Fresnel lens as primary optical element and a truncated ball lens as secondary optical element. Test results show that the concentrator with power generation efficiency of 30.1% and acceptance angle of 0.73° can be obtained. Additionally, temperature effects of SOG lens on power generation are also studied.

1. Introduction

Various measures should be taken to minimize energy cost (€/kWh) and improve reliability of the concentrated photovoltaic system. High concentration photovoltaic technology is based on high-efficiency multi-junction solar cells, concentrating optical system and sun tracking technique. Multi-junction solar cells play an important role in the realization of high energy conversion efficiency. A concentrating optical system with high concentration ratios should be employed to reduce use of solar cells due to its high cost. In the field of CPV cells, three-junction solar cell can reach efficiencies up to 44.4% (Sasaki et al., 2013), EMCORE announced a four-junction inverted Metamorphic Solar Cell with internally measured efficiencies of ~47% (Miller et al., 2014). Huang et al. proposed an upright MM 5J solar cell with an ideal efficiency of as high as 53.9% calculated at 1000 suns and a practical maximum efficiency of 46.2% estimated at 1500 suns (Huang and Yang, 2015). Besides, a concentrator with optimized non-imaging optical systems can also reduce the cost of CPV systems. A desired concentrating optical system should include high optical efficiency, wide acceptance angles and good irradiance uniformity (Benítez et al., 2010; Renzi et al., 2017). The optical efficiency of the concentrator is one of the key factors that affect the cost performance ratio of CPV technology. The acceptance angle, defined as the incident angle at which the concentrator collects 90% of the on-axis power. Wide acceptance angle can greatly relax assembly and alignment tolerances and tracking tolerances, but lack of irradiance uniformity may affect the efficiency and long term reliability of the cell (Baig et al., 2012).

With continuous development of CPV technology, the CPV modules tend to be thinner and more compatible with automatic manufacturing. The main considerations are as follows: (1) although modules with large size concentrating lens and high concentration ratio can reduce the cost, the subsequent installation, transportation and labor cost will account for a large proportion of the total cost; (2) automatic production can not only improve the production efficiency, but also reduce the labor cost. Ball lens as second optical element (SOE) (Ferrer-Rodríguez et al., 2017; Victoria et al., 2009; Fu et al., 2010; Davies, 1993) is widely used in small-sized concentrated modules because of its low production cost (Clark and Wanser, 2001; Lv et al., 2006). The ball lens can be fixed on the surface of the solar cell by optical coupling (Baig et al., 2015, 2014, 2010) or mechanical mounting (Huang and Xu, 2017). For receiver assembly package with optical coupling, there are several disadvantages: (1) difficult positioning control due to point contact between full ball lens and cell, (2) possible damage to the cell grid lines as a result of point contact between ball lens and cell, (3) thick silicone bonding layer (of up to 0.5 mm) between ball lens and cell leading to potential reliability concern. Mechanically mounting the ball lens on the receiver was previously proposed in order to reduce the risk of failure of long term reliability (Huang and Xu, 2017). However, the ball lens with anti-reflection coatings on its top and bottom surfaces should be soldered on a mechanical frame of Kavar alloy leading to the

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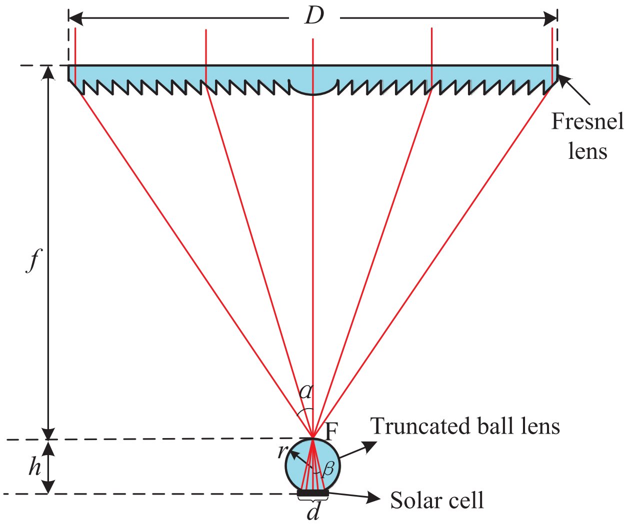

Fig. 1. 2D schematic drawing of concentrating optical system consisting of Fresnel lens, truncated ball lens and solar cell.

energy cost increase of about 5% compared with that using optical coupling.

In this work, we intend to investigate a new CPV optical system with truncated ball lens (Liao et al., 2015; Chen et al., 2004) as secondary optical element to reduce cost of the receiver assembly and improve long term reliability. The truncated ball lens is a glass ball lens with flat bottom surface for receiver assembly which can effectively reduce the silicone usage for bonding layer and hence minimize the system reliability risk in addition to the cost of silicone. Furthermore, the bottom surface the truncated ball lens can be identified easily by CCD camera, which makes it possible to realize automated process of receiver assembly.

2. The proposed concentrator design

A new CPV optical device was proposed and investigated with a flat Fresnel lens as the primary optical element, a truncated ball lens as the secondary optical element and a triple-junction solar cell, as shown in Fig. 1. The schematic view of the central wavelength of each junction of triple-junction solar cell (top sub-cell spectrum: 360–650 nm; middle sub-cell spectrum: 650–900 nm; bottom sub-cell spectrum: 900–1700 nm) at incident angle of 0° and 0.8° are shown in Fig. 2. To balance the irradiance uniformity on three sub-cells and improve the tolerance of the system, the design wavelength of 505 nm is selected in the concentrating optical system, and the focal point generated by the Fresnel lens is located on the top surface of truncated ball lens.

As shown in Fig. 1, a parallel light beam is normally incident onto the surface of Fresnel lens and then focused onto the truncated ball lens. The Fresnel lens is of square aperture with side length of *D*, focal length of *f*, the radius and height of truncated ball lens is *r* and *h* respectively and the side length of solar cell of *d*. *α* is an angle between the edge ray of focusing spot and optical axis, the corresponding refraction angle *β* is given as follows

$$\beta = a\sin\left(\frac{n_1 \sin\alpha}{n_2}\right) \tag{1}$$

$$\alpha = a\tan\left(\frac{D}{2f}\right) \tag{2}$$

$$\tan\beta = \frac{d}{2h} \tag{3}$$

Here, n_1 and n_2 represent refractive index of air and ball lens, respectively, The height of truncated ball lens can be obtained from Eqs. (1)–(3)

$$h = \frac{d}{2\tan\left[a\sin\left(\frac{n_1 \sin(\mathrm{atan}(D/(2f)))}{n_2}\right)\right]} \tag{4}$$

We define the diameter of bottom surface of truncated ball lens to be equal to the side length of solar cell and the radius of truncated ball lens is taken to be

$$r = \frac{4h^2 + d^2}{8h} \tag{5}$$

3. Simulation results for the concentrator

Simulation results are presented for the concentrator with geometrical concentration of 625× and f/1.68. Ray-tracing simulations were performed under the following conditions: AM1.5d solar spectrum with the divergence angle of sunlight (± 0.265°). Silicone-On-Glass (SOG) lens is used for the primary optical element, and it consists of a silicon layer (n ≈ 1.41) and a glass super-strate (n ≈ 1.52) without anti-reflection coating. SOE is made of Chinese CDGM H-K51 glass (n ≈ 1.51) with anti-reflection coating.

Fig. 3 shows the simulated optical efficiency versus the incident angle for each sub-cell. The acceptance angle of top, middle and bottom cell are 0.73°, 0.76° and 0.82° respectively. As for the system is limited by top cell, the misalignment performance of this designed system should be referred to the top cell. From the solid line in Fig. 3, it is noted that the curve shows maximum efficiency of above 95% until it reaches around 0.6° of deviation, ensuring a higher tolerance of optical system. Fig. 4 represents the irradiance profile on each junction of the solar cell for different misalignment angles. At normal incidence, the

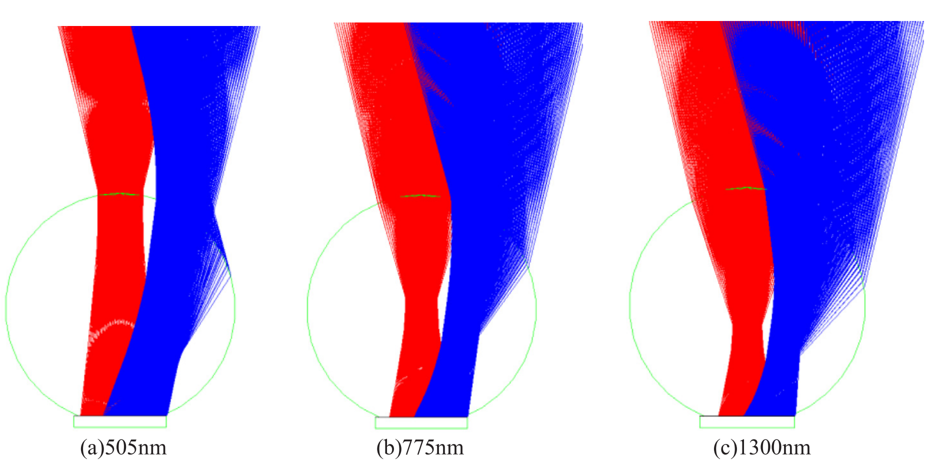

Fig. 2. Ray tracing of 625 × concentrator with truncated ball lens as the secondary optical element for incident angle of 0°(red rays) and 0.8°(blue rays), for different wavelengths set in the simulations: (a) 505 nm; (b) 775 nm; and (c) 1300 nm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)