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Invited paper

Concept design and simulation of a concentration lens with uniform square irradiance

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ABSTRACT

A planar concentration lens comprised of square and rectangular lenses for solar concentration application is presented. The design of the concentration lens was based on the concept of Fresnel lens and the layout of the square light spot was proposed to match the receiving area. The uniformity of the light spot was determined by the structure of the concentration lens, which has different structures for different design wavelengths. The uniformity of the light spot and concentration ratio of the concentration lens were simulated. The numerical results indicate that the concentration ratio and uniformity of the light spot decrease with the increment of the wavelength. In order to improve the performance of the concentration lens, a novel hybrid wavelength structures was designed. The analysis results reveal that both the spot uniformity and concentration ratio of such a novel concentration lens were insensitive to the wavelengths variation. In addition, the angular tolerance of the concentration lens was discussed for different incident angles.

1. Introduction

Photovoltaic (PV) power generation systems have attracted widespread attention over the years with the development of emerging renewable energy technologies. However, so far it is difficult to compete with coal fired power generation systems because of the high costs. The key to the widespread use of photovoltaic power generation systems is to reduce costs. In order to enhance the efficiency and reduce costs of photovoltaic cell systems, concentration devices are introduced. Compared to PV cells, inexpensive concentration devices can improve irradiance intensity efficiently to reduce the area of PV cells. Photovoltaic power generation systems with concentration devices are called concentrated photovoltaic (CPV) systems. The most important components of CPV system are concentration devices and PV cells. Generally, the technologies of concentration devices can be divided into two types: reflective concentrators and refractive concentrators. Reflective concentrators [1,2] are composed of reflective mirrors, while refractive concentrators are composed of refractive lenses. The most commonly used refractive lens to concentrate sunlight is Fresnel lens [3–8], which has excellent properties of light weight, low cost and easy to manufacture [9,10]. However, the Fresnel lens' intrinsic structure leads to highly concentrated irradiance distribution that vividly called hot spot on receiving area. The problems the hot spot caused mainly in three aspects: (1) The conversion efficiency of PV cells decreases as the open-circuit voltage decreases [11]; (2) Hot spot may burn PV cells and shorten the life of PV cells; and (3) Thermal energy management faces severe challenges. Non-uniform irradiance distribution can be optimized by improving the Fresnel lens' structure, and then a circular light spot was obtained by Z. Zhuang and F. Yu [12]. Modular facet Fresnel lenses [13] and the compound lens [14] achieved uniform irradiance distribution on the receiving area with moderate concentration ratio. The uniformity can be further improved by using two-stage concentrator which is comprised of a primary optical element (POE) and a secondary optical element (SOE) [15]. To the authors' knowledge, the most uniform light spot can be achieved by Kohler integrator in SOE [16–18]. Total internal reflection–refraction (TIR-R) concentration lens is one of the two-stage concentrators and can form a uniform light spot and get high concentration ratio [19]. Among the concentrators mentioned above, although the irradiance distribution of two-stage concentrators is more uniform irradiance distribution than that of the one-stage concentrators, using a SOE increases the manufacturing cost of the concentration systems and the difficulty of installation. The free-form boundary surface design method was used in the design of the SOE for high concentration ratio (more than 300) [20]. One-stage concentrators have the advantage of low cost, easy installation and more suitable for low concentration ratio and middle concentration ratio (less than 300). Therefore, improving the uniformity of the irradiance distribution of one-stage concentrators is important. In concentration systems, a

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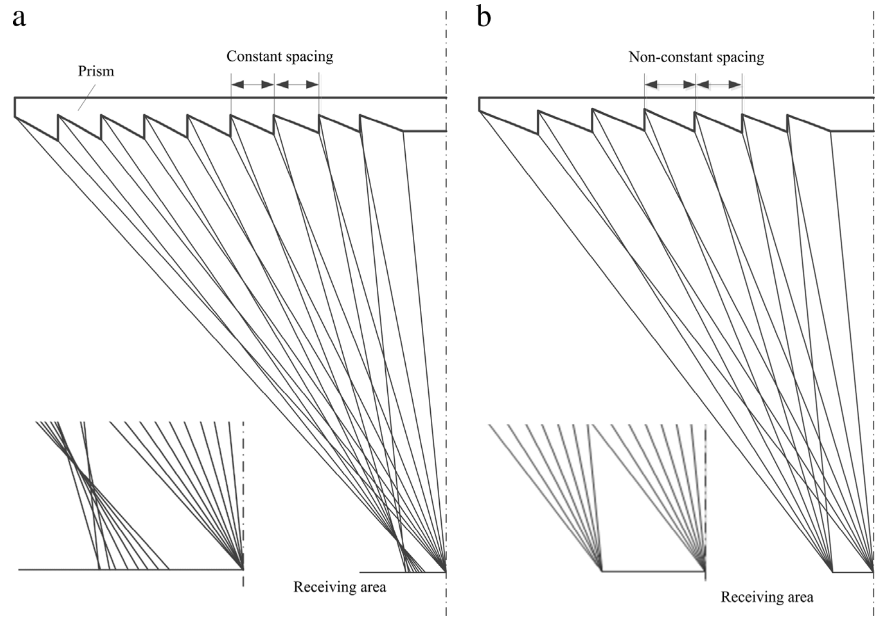

Fig. 1. Cross section view of a Fresnel lens with (a) constant spacing prisms, and (b) non-constant spacing prisms.

uniform irradiance distribution is easily obtained for monochromatic wavelength than that for polychromatic wavelength. The irradiance distribution and concentration ratio vary with wavelength. The concentration lens forming uniform light spot, which is insensitive to the wavelengths variation, can promote the utilization of solar energy and can be applied to alleviate the hot spot inside PV modules.

In this paper, a novel concentration lens which has uniform irradiance distribution on the receiving area in a broad wavelength range is presented. The concentration lens is a one-stage concentrator comprised of square and rectangle lenses. The irradiance distributions and concentration ratios are studied for different wavelengths with the ray tracing simulation. A hybrid wavelength structure of the concentration lens is designed to improve the optical efficiency and the uniformity of the receiving area. The concentration lens can be divided into four parts that are designed for different wavelength structures. The percentage of energy illuminating on the receiving area and the uniformity of the light spot are theoretically investigated for different incident angles within the wavelength range from 400 to 1600 nm.

2. Design of non-constant spacing prisms and square lenses

Fresnel lens is usually made of polymethylmethacrylate (PMMA), which is one of the most widely used plastics in concentrated applications of solar energy because PMMA has the characteristics of high light transmittance, light weight, and low cost. In general, the light spot of Fresnel lens is non-uniform and the intensity distribution on the center position of the receiving area is much higher than that on the edge of the receiving area. The most important reason for the non-uniformity of the light spot is that the facets structure of Fresnel lens is circular. Fresnel lens designed with constant spacing prisms structure is depicted in Fig. 1(a). Each prism has same prism length and different prism angle (here the prism angle is defined as the angle between the horizontal plane and the slope of the prism). The prism angle increases from the center position to the edge of Fresnel lens. The prisms refract light to form different size spots on receiving area. The prism away from the center forms smaller spot size than the prism near the center. In order to form spots with the same size, a Fresnel lens with non-constant spacing prisms structure is proposed in Fig. 1(b). These prisms have different prism lengths and prism angles to refract light to form spots with the same size.

The design of the Fresnel lens with non-constant spacing prism structure is based on two structure parameters (the prism angle and the prism length) that determined by material refractive index n, the receiving area size d, and the focal length f. The design sketch of the non-constant spacing prism structure is illustrated in Fig. 2. The prism angle is denoted as α which is equal to the incident angle β. The corresponding refraction angle is expressed by β'. The prism length and prism height are represented as l and y. In addition, each prism has its number i. Therefore, l_i and α_i represent the ith prism's length and the ith prism's angle, respectively.

The difference between the incident angle and the refraction angle (β'-β) is given as follows:

$$\tan(\beta_i' - \beta_i) = \frac{\sum_{k=1}^{i} l_k}{f}. \tag{1}$$

The relationship between the prism length l_i and the receiving area size d yields as,

$$l_i - x_i = d \tag{2}$$

the meaning of x_i is the difference between the prism length l_i and the absorber surface size d.

Therefore, the sum of the prism lengths also can be expressed as

$$\sum_{k=1}^{i} l_k = l_i + \sum_{k=1}^{i-1} l_k = x_i + d + \sum_{k=1}^{i-1} l_k. \tag{3}$$

Usually, the term $(d + \Sigma l_i)$ is much greater than x_i, and Eq. (1) can be approximated by Eq. (4),

$$\tan\left(\beta_i' - \beta_i\right) = \frac{\sum_{k=1}^{i} l_k}{f} = \frac{x_i + d + \sum_{k=1}^{i-1} l_k}{f} \cong \frac{d + \sum_{k=1}^{i-1} l_k}{f} \tag{4}$$

$$\beta_i' - \beta_i = \arctan\left(\frac{d + \sum_{k=1}^{i-1} l_k}{f}\right). \tag{5}$$

According to Snell's law given as Eq. (6),

$$\frac{\sin \beta_i'}{\sin \beta_i} = n \tag{6}$$

there is the following relationship,

$$\tan \beta_i = \frac{\sin\left(\beta_i' - \beta_i\right)}{n - \cos\left(\beta_i' - \beta_i\right)}. \tag{7}$$