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Improved irradiance distribution on high concentration solar cell using free-form concentrator

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Abstract

This study proposes a free-form (FF) surface creation (FFSC) method to optimize the profile of a FF solar concentrator such that each incident ray is directed to a user-specified point on the solar cell surface. The light ray paths within the concentrator system are analyzed using an exact analytical model and a skew-ray tracing approach. The effectiveness of the proposed method is demonstrated numerically by comparing the irradiance uniformity performance of five concentrator systems, namely a single FF reflector (single-FF), a standard parabolic reflector with a single FF reflector (SP + FF), a single-SP reflector (single-SP), a dual-SP reflector (dual-SP) and a SP + standard hyperbolic (SP + SH). The simulation results show that the concentrator systems containing FF reflectors achieve a significantly better irradiance uniformity than those based on conventional SP and SH reflectors.

Keywords: Solar cell; Concentrator; Parabolic; Skew-ray tracing; Free-form

1. Introduction

Concentrated photovoltaic (CPV) systems are a promising source of green energy in which lenses or curved reflectors are used to enhance the intensity of the sunlight incident on the surface of a solar cell. Andreev et al. (2004) developed an all-glass PV module comprising an array of small-aperture lenses placed between a set of primary Fresnel lens concentrators and the solar cell panel. Nilsson et al. (2007) developed three micro-structured reflectors for improving the illuminance uniformity and concentration ratio of a stationary asymmetric parabolic concentrator system. Garcia-Botella et al. (2006) showed that elliptical concentrators provide many new capabilities compared to reflectors with symmetrical or free-form surfaces. Maruyama and Osako (1999) proposed a wedge-shaped concentrator in which the light was focused on the solar cell by means of specular reflection at the rear surface and refraction or total internal reflection at the front surface. Maruyama and Minami (2003) showed that the collector efficiency of a spherical solar cell is higher than that of a conventional flat plate cell due to the enhanced scattering of the reflected light from neighboring cells in the array. Morimoto and Maruyama (2005) proposed a static solar concentrator consisting of vertical flat plate solar cells and a white/transparent switchable bottom plate. McIntosh et al. (2007) showed that the optical concentration of cylindrical luminescent solar concentrators (LSCs) is higher than that of square-planar LSCs; particularly when the multiple reflections between neighboring LSCs are taken into account. Huang et al. (2010) presented a novel solar concentrator in the form of a circular prism array for use in either standalone applications or in

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Nomenclature

$S\theta$	$\sin(\theta)$
$C\theta$	$\cos(\theta)$
$(xyz)_0$	world coordinate frame
$(xyz)_i$	coordinate frame imbedded in ith boundary surface
i	boundary surface index, $i = 1, 2, \ldots, n$
$\mathbf{r}_i$	ith boundary surface
$\mathbf{P}_i$	incidence point on $\mathbf{r}_i$
$\boldsymbol{\ell}_i$	unit directional vector of light ray reflected/refracted at ith boundary surface
${}^j\mathbf{A}_i$	pose of coordinate frame $(xyz)_i$ with respect to coordinate frame $(xyz)_j$
${}^i\mathbf{S}_i$	generating curve of ith axial symmetric boundary surface
α_i	rotation angle of generating curve ${}^i\mathbf{S}_i$ about y-axis
β_i	argument of generating curve ${}^i\mathbf{S}_i$ in xy-plane
f_i	focal length of standard parabolic (SP) reflector
c_i, d_i	coefficients of standard parabolic (SP) reflector generating curve
s_i	coefficient set as either +1 or −1 such that cosine of incidence angle is greater than zero
λ_i	magnitude of vector $\overrightarrow{\mathbf{P}_{i-1}\mathbf{P}_i}$
e_{i0} to e_{i4}	coefficients in Eq. (9a)
θ_i	incidence angle of incoming ray on boundary surface $\mathbf{r}_i$
$D_{entrance}$	circular entrance width of concentrator
L_{cell}	side-length of square solar cell
U_{sun}	solar irradiance
W_{beam}	average power carried by each bundle of solar rays
U'_τ	actual irradiance distribution on solar cell
U_{ideal}	ideal irradiance distribution on solar cell
$K_{concentration}$	concentration magnification

Abbreviation

FF	free-form
SP	standard parabolic
SH	standard hyperbolic
FFSC	free-form surface creation

conjunction with a second solar-energy focusing module. Korech et al. (2007) proposed a microfabricated dielectric optical design to eliminate the shading losses caused by the metal fingers on the active area of concentrator solar cells. Leutz and Annen (2007) used a reverse ray tracing method and a solar radiation model to evaluate the yearly energy collection efficiency of a stationary solar concentrator. Sarmah et al. (2011) used a ray tracing approach to design and evaluate three stationary dielectric asymmetric compound parabolic concentrators (DiACPCs) with acceptance half-angles of (0°/55°), (0°/66°) and (0°/77°), respectively. Tao et al. (2011) developed a solar concentrator system incorporating a compound-surface parabolic concentrator, a secondary reflection plane mirror, and a parabolic trough concentrator. Sheng et al. (2011) performed finite-difference time-domain (FDTD) simulations to optimize the surface texture of thin-film Si solar cells. Leutz et al. (1999) designed a convex-shaped non-imaging Fresnel lens for use as either a temperature generator in evacuated tube-type solar concentrators or a solar concentrator in PV applications. Sheng et al. (2013) showed that the power output obtained from thin-film, micro-scale GaAs solar cells mounted on top of LSC substrates is higher than that obtained from conventional LSCs with side-mounted cells. Timinger et al. (2000) proposed an optical measurement method for determining the geometry and surface reflectivity of non-imaging radiation concentrators.

In order to improve the irradiance uniformity, several investigations have been proposed. Ryu et al. (2006) proposed a new solar concentrator utilizing modularly faceted Fresnel lenses to achieve a uniform intensity on the absorber plane. Gonzalez-Garcia et al. (2009) proposed the lenses and mirrors which were designed by a set of concentric spherical rings that produced a desired energy distribution in the focal plane. Bergamin and Sammaraee (2010) proposed a method to improve the light distribution of solar cells by modifying the surface of the glass cover. Simon and Meyer (2010) analyzed the non-uniform surface temperature distribution of solar cells, and it results in localized heating (hot-spot) and damages the solar cell. Yu et al. (2014) improved the flux distribution as much as possible by changing the aiming points of different groups inside a cavity receiver. Rabady and Andrawes (2014) proposed a concentrator design, which was accomplished by solving a second order differential equation numerically, to guide the sunlight onto the receiver uniformly.

The primary function of a solar cell concentrator system is to focus the incident sunlight on the surface of the solar cell. However, given a non-uniform distribution of the incident sunlight, localized over-heating of the solar panel may occur; giving rise to a reduced photo-electro transition rate and, in extreme cases, device damage. Consequently, sophisticated concentrator designs are required. Accordingly, the present study proposes a free-form surface creation (FFSC) method to optimize the generating curve of the reflector such that the incident rays are directed to specific points on the following boundary surface. The FFSC method is used to design two concentrator systems, namely one system containing a single free-form (FF) reflector and a second system containing a standard parabolic reflector and