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Featured Letter

Conjugate refractive–reflective based building integrated photovoltaic system

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ABSTRACT

Building Integrated Concentrating Photovoltaic (BICPV) systems make use of optical elements to concentrate the incoming solar radiation on small-sized solar cells with the aim of integrating PV technology into the building. We present a novel conjugate system designed to utilize the merits of both reflective and refractive optics. The optical geometry under study is a dielectric based three-dimensional cross compound parabolic concentrator (3DCCPC) enveloped by a reflective geometry of similar shape whilst maintaining an air gap between them. Monte Carlo ray-trace simulations are used to model and optimize the system configuration. The theoretical analysis shows that the optical performance of the system can be improved by 11% whilst maintaining an air gap of 0.1 mm between the reflective and the refractive surfaces. Experiments are carried out by making a prototype of the proposed system to evaluate the proof of concept. A maximum power ratio of 2.76 was found under standard testing conditions at an incidence angle of 10°. Results show that the average power output from the proposed system increases by 5.46% compared to its predecessor.

1. Introduction

Integration of concentrating photovoltaic systems into building architecture is referred to as Building Integrated Concentrating Photovoltaics (BICPV). Several systems have been presented in the past decade demonstrating the potential of this technology [1–4].

The most popular design is the Compound Parabolic Concentrator (CPC) which generally comprises of two reflective shaped parabolas formed by rotating their axis through a certain design angle (also known as the acceptance angle, θ_a) and translation of its origin. All the rays entering the concentrator at angles less than the acceptance angle reach the exit aperture. This design was superseded by asymmetric designs that expand building integration possibilities [4,5]. Improvements on these systems were presented recently [1,6], where the use of a reflective boundary was made along the outer surface of the CPC to trap the light escaping the concentrator surface. Further developments were made on the BICPV system using a Three Dimensional Cross Compound Parabolic Concentrator (3DCCPC) using both reflective [7] and refractive [2] based geometries.

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2. System description

In the present study, we introduce a new type of system which incorporates the benefits of both reflective and refractive based concentrators. A Conjugate Cross Compound Parabolic Concentrator (CCCPC) designed for a 3.6× geometric concentration is presented which essentially consists of a dielectric 3DCCPC enveloped by a reflective surface of the same shape to trap any escaping rays from the dielectric. Fig. 1 shows the different components of the system.

2.1. Optical simulation

Ray-trace simulations were carried out using the APEX® software package under standard AM 1.5G spectrum. Fig. 2(a) shows the ray-trace analysis of a 3DCCPC at 0° incidence. Incoming rays undergo total internal reflection and reach the solar cell. During this process some rays escape through the edges of the concentrator. Trapping these escaping rays using a reflecting surface with a small air gap can improve the performance. The air gap is very important to maintain the TIR effect. Fig. 2(b) shows the rays trapped by the reflective surface which is fitted along with an air gap. Some of the rays still escape from the edges of the concentrator, which essentially depend on the amount of air gap between the two surfaces.

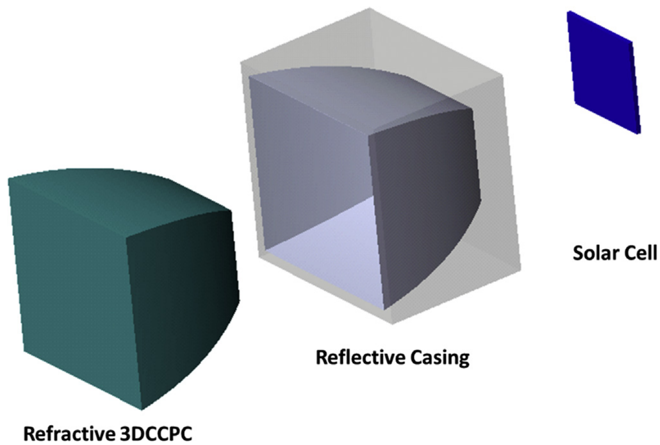

Fig. 1. Components of the Conjugate system.

2.2. Materials & manufacture

High efficiency Laser grooved Buried contact [8] solar cells were used in the study. These cells are processed using commercially available p-type boron doped Cz silicon wafers. Using a direct laser process trenches are formed on the front of the cell which are then Ni-Cu plated to form buried contacts. Further details on the solar cell manufacture can be found in the appendix. Clear polyurethane material crystal –clear 200 ®, due to its excellent transmission and dielectric properties, is used to prepare the concentrating element. The casing was prepared using 3D printing process. Once printed, the reflective film was attached along the inner surfaces of the sleeve.

3. Impact of air gap

The illumination flux reaching the solar cell after concentration changes considerably while using the reflective surface of the casing around the 3DCCPC. This increment in the energy flux helps in the improvement of the optical efficiency of the system. Fig. 3(a) shows a spatial distribution of the energy flux increment (ΔG) obtained while using the reflective sleeve at incident angles of 45°. There is an average increment of 40.3 W/m^2 at 45° incidence respectively with an air gap of 600 μm between the reflective and refractive surfaces. The optical efficiency is a key parameter in determining the performance of a concentrating photovoltaics system and defined as shown in Eq. (1).

$$\eta_{opt} = \frac{G_{with}}{G_{without}} * \frac{1}{C_g} \tag{1}$$

A parametric study was carried out by changing the air gap between the concentrator and the reflective surface at different incident angles. The initial refractive based system reported earlier is also presented for comparison purposes.

Fig. 3(b) shows a comparison of optical efficiency for the system with varying air gaps between the reflective and refractive geometries. The air gap was varied from 0 to 1 mm. There is a sudden boost in the optical efficiency when the reflective surface is directly in contact with the outer periphery. The optical performance, however, is found to reduce the acceptance angle of the system. The refractive system was expected to have a maximum of 73.5% efficiency by itself. Creating an air gap between the surfaces increases both the optical efficiency and the acceptance angle of the system. Increasing the air gap reduces the optical efficiency due to increased ray travel and rays being rejected out of the system. A maximum optical efficiency of 84% could be achieved with an air gap of 0.1 mm at an incidence angle of 25°.

4. Results

4.1. Electrical performance

The experimental setup typically consists of a light source generating collimated light with a standard AM 1.5G spectrum at 1000 W/m^2. Four different system measurements were carried out using the same solar cell at different incident angles using a special setup [2]. The systems include the following: (i) Bare solar cell; (ii) An Initial Refractive based 3DCCPC system; (iii) New Refractive 3DCCPC system and (iv) Conjugate system.

Fig. 4(a) shows the variation of the Isc at different incident angles. Under normal incidence, the conjugate system has the highest value of 102 mA compared to 89 mA reported earlier [2] which shows a 14.6% increase in the short circuit current value. The new refractive system produced using the current manufacturing method is found to give improved results compared to the initial refractive system and has a short circuit current of 96 mA.

The performance increment is reflected across the entire range of the incidence angles up to 60°, where both the systems become the same. The variation of the open circuit voltage is shown in Fig. 4(b). The open circuit voltage (Voc) of all the different systems

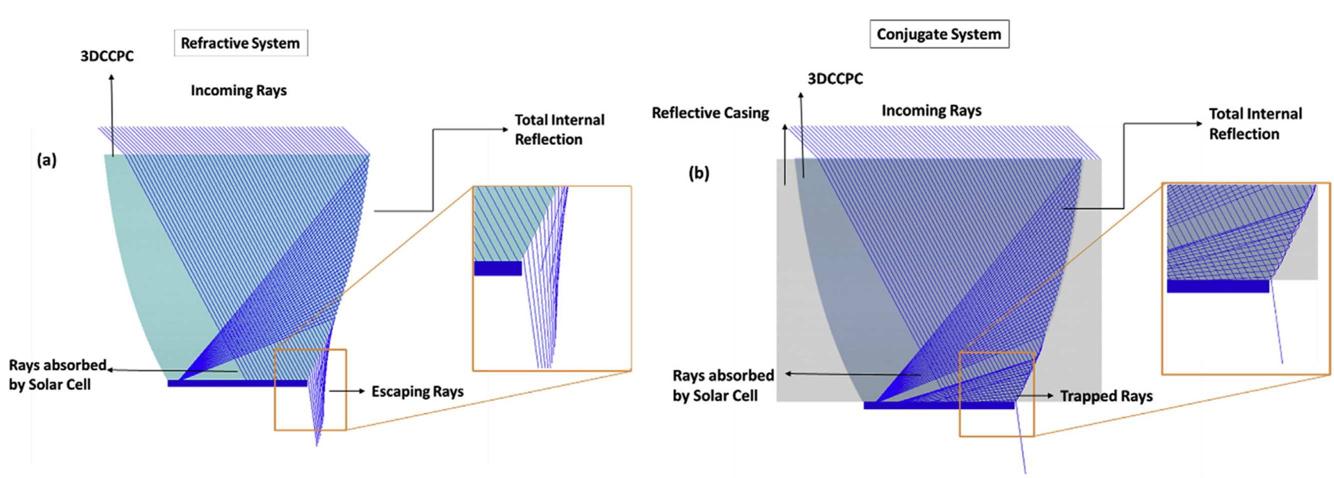

Fig. 2. (a) Ray-trace analysis of the dielectric 3DCCPC showing the rays escaping through the surface of the concentrator (b) Ray-trace analysis of the conjugate system.