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Performance analysis of a novel rotationally asymmetrical compound parabolic concentrator

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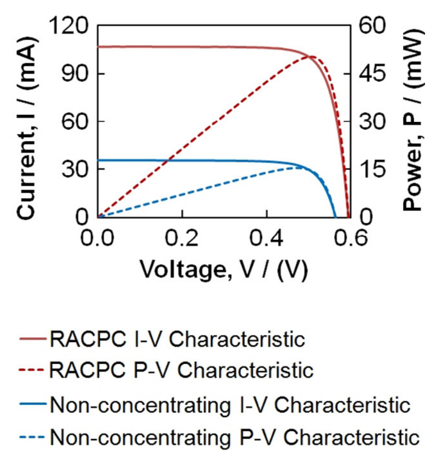
HIGHLIGHTS

- A novel rotationally asymmetrical compound parabolic concentrator is presented.
- The electrical and optical performances are investigated.
- It increases the maximum power output by 3.33× and the short circuit current by 3.01×.
- The RACPC is an attractive alternative design for the BICPV systems.

GRAPHICAL ABSTRACT



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ABSTRACT

The low-concentration photovoltaic (LCPV) system has been identified as one of the potential solutions in lowering the overall installation cost of a building integrated photovoltaic (BIPV) system. This paper evaluates the performance of a novel type of LCPV concentrator known as the rotationally asymmetrical compound parabolic concentrator (RACPC). A specific RACPC design with a geometrical concentration ratio of

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3.6675× was fabricated and integrated with a 1 cm by 1 cm monocrystalline laser grooved buried contact silicon solar cell. This design was tested indoors to evaluate its current–voltage (*I–V*), angular response and thermal characteristics. Under standard test conditions, it was found that the RACPC increases the short circuit current by 3.01× and the maximum power by 3.33× when compared with a bare solar cell. The opto-electronic gain from the experiment showed good agreement when compared with the simulation results, with a deviation of 11%.

1. Introduction

Solar photovoltaic (PV), which is one of the technologies that harnesses solar energy by converting the sunlight directly into electricity, grew by more than 100 folds from 2000 to 2013, with a cumulative capacity of 139 GW by the end of 2013 [1]. One of the reasons for this growth has to do with the fact that the governments of several countries have taken the right steps to stimulate the adoption of solar PV technologies. With regards to policy one of the most effective ones is known as the feed-in tariff (FiT) scheme [2–13]. This scheme pays a consumer a specific tariff per kW h of electricity generated from solar PV technology for a duration of time [8], and is now being enacted in more than 80 countries [2].

Despite the growth of solar PV, the Intergovernmental Panel on Climate Change (IPCC) indicates that 'its share of primary energy supply has remained relatively constant' [14]. Therefore more needs to be done to ensure that renewable technologies, especially solar PV, are more widely adopted in order to reduce climate change.

One of the problems that surrounds the PV technology is its high cost of implementation, which according to the recent data from the International Energy Agency (IEA) ranged between £830 and £16,000 per kW[1] [15]. The largest proportion of the cost (approximately 45%) was due to the expensive PV material used in the fabrication of the module [15]. It is argued that by reducing the usage of PV material in a PV module, it is possible to achieve a cheaper PV system, which could further attract more consumers into opting and installing this technology [16–18].

A possible way to reduce the amount of expensive PV material and therefore the cost of the PV modules and the PV systems is by using a solar concentrator – a device (mainly constructed from a low cost refractive and/or reflective material) that focuses the solar radiation from a large entrance aperture area into a smaller exit aperture area where a solar cell is attached [16–18]. This allows the system to generate a similar or higher electrical output than a conventional PV system, while at the same time using only a fraction of the PV material.

Several researchers have explored various concentrator designs since the late 1960s. A low-concentration photovoltaic (LCPV)[2] system is more suitable for building integration since it has a wider half-acceptance angle which eliminates the need for any electromechanical tracking of the sun [19,20], it increases the optical gain under both direct and diffuse radiation [19] and it does not require any active cooling requirement [21]. Uematsu et al. [22] developed a flat-plate static concentrator (FPSC) that was able to increase the maximum power output by 2% when compared with a conventional PV module. Gajbert et al. [23] studied a reflective parabolic concentrator and calculated that the design could boost the annual electricity production by 72% compared to a non-concentrating design. Garcia et al. [24], on the other hand, experimented on a V-trough concentrator and obtained a maximum power gain of up to 1.5 when compared with a non-concentrating panel. Yoshioka et al. [25] constructed a 3D refractive static concentrator and obtained an optical gain of 2.3× when compared with a bare cell. Muhammad-Sukki et al. [18,26–31] investigated the performance of an extrusion of a dielectric totally internally reflecting concentrator (DTIRC) and concluded that their design could increase the electrical output by nearly 5 times when compared with a non-concentrating system. Ramirez-Iniguez et al. [32] patented a variation of the DTIRC, which is a rotationally asymmetrical DTIRC and have demonstrated that their design could achieve an opto-electronic gain of 4.2× when compared with a bare PV cell [33–35]. Mallick and Eames [36] investigated a reflective asymmetrical compound parabolic concentrator (CPC) which improved the power concentration ratio of the panel by 2.1 times when compared with a similar non-concentrating panel. Another CPC design studied by Mammo et al. [37] known as the crossed compound parabolic concentrator (CCPC) generated 3 times more maximum power than the one generated by a non-concentrating system.

This paper proposes a new variation of CPC design for use in building integrated photovoltaic (BIPV) systems. This concentrator is known as a rotationally asymmetrical compound parabolic concentrator (RACPC). This paper aims at evaluating the electrical performance of the concentrator under standard test conditions. The process to design the concentrator as well as the theoretical and simulation work related to this concentrator design have already been covered in detail by the authors in [38]. Section 2 summarises the steps involved in the design of the concentrator. The fabrication and assembly of the prototype is discussed in Section 3. The experimental setup is discussed in Section 4. Section 5 presents a discussion of the results from the experiments, and finally the conclusions are presented at the end of the paper.

2. RACPC design

The RACPC is a new variation of the CPC. The design utilised similar algorithms to generate the dielectric totally internally reflecting concentrator (DTIRC) by Ning et al. [39], in which they proved that the CPC is a DTIRC with a flat entrance aperture. A MATLAB® code was written to create the RACPC by taking into account the desired input parameters: the total height of the concentrator, (*HTot*), the half-acceptance angle (θ_a), the length of the PV cell (L_{PV}), the width of the PV cell (W_{PV}), the trial width of the entrance aperture (d_1), the index of refraction of the material (n) and the number of extreme rays (N).

The steps in producing this design has been presented in detail in [38]. Fig. 1 helps to explain the process to design the RACPC. Based on the input parameters, the MATLAB® programme produces the first 2D-symmetrical design, which is plotted at 'Position 1' in Fig. 1. Then, a new CPC design is produced, with each new design is computed by incrementing the angle of rotation of the cross-sections by 1° and by using the predetermined exit aperture value (see 'Positions 2, 3 and 4' in Fig. 1). The process stops when a 180° rotation around the *y*-axis is completed. The programme generates the point cloud coordinates of the RACPC and obtains some important parameters of the design, i.e. the geometrical concentration gain, the half-acceptance angle and the maximum width of the entrance aperture of the concentrator.

[1] Based on the conversion rate carried out on 10/11/2014, USD1.00 is equivalent to £0.63 [50]. This value is used throughout this paper.

[2] An LCPV is a system that incorporates a concentrator with a geometrical gain of less than 10×.