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Optical and Electrical Performance Evaluation of the Crossed Compound Parabolic Concentrator Module for the Application of Ultra-High Concentrator Photovoltaic System

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Abstract. This paper presents the performance evaluation in terms of optical and electrical characteristics of the crossed compound parabolic concentrator (CCPC) module for the application of the ultra-high concentrator photovoltaic (UHCPV) system. The CCPC module is the integration of a dielectric-filled 3D CCPC lens and a multi-junction solar cell (MJSC) module. The optical efficiency of the refractive lens has been evaluated through the ray-tracing simulation technique by including all the possible optical losses at each component level, and the output current of the MJSC module has also been calculated in accordance with its spectral response to the wavelengths range from 300 nm to 1800 nm. The optical efficiency of CCPC lens itself is determined to be 69.33%. With reference to the output current of the MJSC module without a CCPC lens, an optical concentration ratio of 4.65 is observed in the simulated result. An indoor experiment has been performed to validate the simulated result, in which an effective optical concentration ratio of 4.57 has been obtained via laboratory measurement. The experimental result is matched well with the simulated result and it shows that the CCPC module has an effective optical efficiency of 76.17% as the geometrical concentration ratio of the CCPC lens is 6.00. The detailed study of CCPC module is good for optimizing the performance of the UHCPV system.

1. Introduction

In recent years, the introduction of multi-junction solar cells (MJSCs) with the proven optical-to-electrical efficiency of 46% has accelerated the research and development of concentrator photovoltaic (CPV) system. Due to the remarkable cost reductions in flat-plate photovoltaic (PV) modules, a CPV system with greatly improved solar concentration ratio (SCR) is indeed a significant strategy to be a highly competitive solution in the solar energy market. By boosting the CPV system to ultra-high concentration ratio, it can dramatically reduce the usage of high-cost solar cells by replacing with inexpensive optics as well as the levelized cost of solar electricity (LCSE). The higher the SCR, the higher the system output power. However, an effective way of solar energy harvesting can be challenging due to the chromatic aberration limits for single material mirrors/lenses. In respect to this issue, an earlier study suggested that by adding homogenizing lenses as secondary optics to the

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system, it is able to break through the boundaries and produce a SCR of more than 1000 suns [1]. Among all types of homogenizing optics, a 3D-CPC is said to be the most ideal as it works perfectly for all light incidences within the desired acceptance angle [2-3]. Thus, Wong et al. has proposed an ultra-high concentrator photovoltaic system using small-scale two-stage non-imaging solar concentrator. This system has the capability to produce an ultra-high SCR (>1000 suns) and a reasonably uniform solar illumination focused onto the MJSCs[4]. The proposed UHCPV system comprises of non-imaging dish concentrator (NIDC) as a primary optical element (POE) and crossed compound parabolic concentrator (CCPC) lens as a secondary optical element (SOE) [4].

The general features of CCPC lens has been discussed in the previous work [4-6], but a detailed performance evaluation on the lens has yet to be studied. In a CPV system, optics are the core components to determine the practicability of the system. A good understanding of the optical characteristics is the key to optimize the performance of a CPV system. Therefore, there is an interest to study the performance of CCPC lens in detailed. In this paper, the detailed characteristics of a CCPC module, a combination of a dielectric-filled 3D CCPC lens and a multi-junction solar cell (MJSC) module, is evaluated in terms of optical and electrical performance by considering several imperfection factors that were neglected in the previous study. The evaluation has been done through computational and experimental methods.

2. Overview of the CCPC Module

Figure 1 shows the illustrative diagram of the UHCPV system, which consists of NIDC and CCPC modules, proposed by Wong et. al [4]. As shown in Figure 1(b), the CCPC modules comprises of CCPC lenses and MJSC modules. Optical adhesive is used to bond the components together. Each receiver module is equipped with MJSC and a bypass diode. The MJSC consists of three layers of different materials connected in series, which is Indium Gallium Phosphide (InGaP), Indium Gallium Arsenide(InGaS) and Germanium(Ge), where each material responds to a different range of the solar spectral irradiance. Figure 1(c) shows the cross-sectional view of the CCPC lens, which possesses with entrance aperture, $2a$ and exit aperture, $2a'$ with the dimension of 24mm and 9.8mm respectively that result in geometrical concentration ratio (GCR) of 6.00. The dimension of the square-shaped exit aperture are designed to match with the dimension of Azur Space 3C44 MJSC used in the module, at which the cell aperture's dimension is 10 mm × 10 mm. The exit aperture of CCPC lens is slightly smaller than the solar cell to avoid low packing factor due to the less active area at the peripheral region of the cell. The angular half acceptance angle, θ_i and length of the CCPC lens is 37.77° and 37.78mm respectively. The CCPC lens are made of Schott B270 Crown Glass due to its high transmissivity and affordable cost.

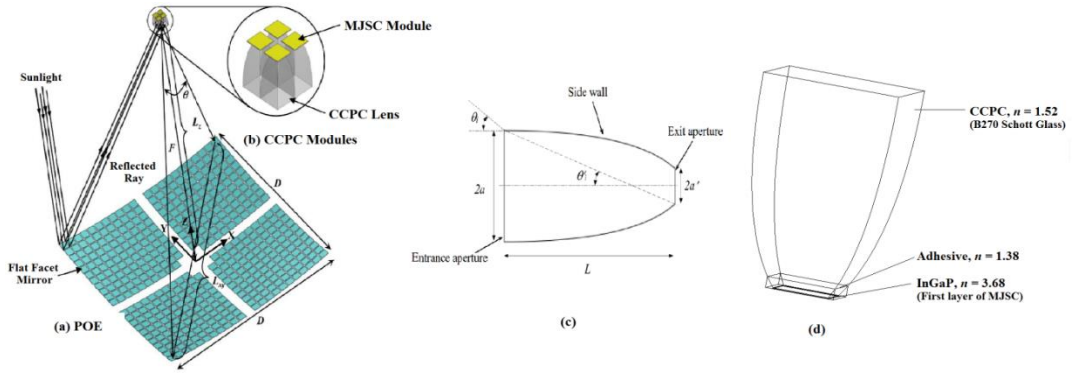


Figure 1. The 3-dimensional view of the proposed ultra-high concentrator photovoltaic (UHCPV) system. (a) Primary optical element (POE), non-imaging dish concentrator (NIDC) (b) Crossed compound parabolic concentrator (CCPC) modules, a combination of CCPC lenses and MJSC modules (c) Schematic diagram to show the dimension of the dielectric-filled CCPC lens (d) Refractive index, *n* of each component level of the CCPC module [4].

3. Performance evaluation of the CCPC Module

With the aid of an opto-mechanical software, Tracepro, a comprehensive optical characterization of CCPC lens has been carried out through the ray-tracing technique by considering all the possible optical losses at each component level, such as Fresnel reflection losses, materials' transmissivity - absorption, edge/corner leakage due to adhesive spillage, and the effect of anti-reflective coating. The Fresnel reflection loss occurs at the interface of two materials when there is any discontinuity of refractive index [7]. Figure 1(d) shows the refractive index, *n* of each component in the model. In this study, Fresnel losses occur thrice in total as there are four different mediums including air. To overcome the big gap between the *n* of Indium Gallium Phosphide (InGaP), which is the first layer of MJSC, and the engaged medium (glass or optical coupler), a bilayer of anti-reflective coating is deployed on the surface of the solar cell to minimize Fresnel reflection losses [8]. A summary of the evaluation process is illustrated in Figure 2.

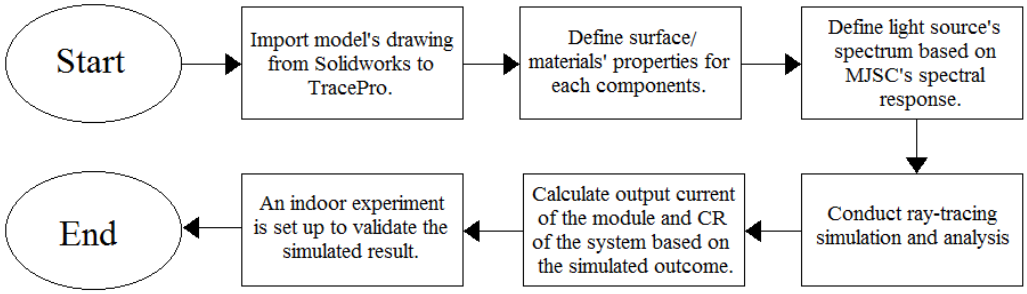


Figure 2. Flowchart to show a process of evaluating the optical and electrical performance of the CCPC module.

It is significant to define the surface and materials' properties data in the simulation. Defining any improper property data may result in inadequate accuracy. Most of the properties data used in the simulation are obtained from TracePro's built-in database while the information that is not included in the library such as absorption coefficient, α and extinction coefficient, *k* of Schott B270 Glass and Indium Gallium Phosphide (first layer of MJSC), the properties data are extracted from the datasheet as provided by the manufacturer. The wavelength of light source is set in a range of 300 nm – 1800 nm in accordance with the spectral response of MJSC. The ray-trace simulation began with a set of parallel light rays approaching the CCPC lens. Once the light rays reached the lens, the light rays undergone the process of reflection, refraction and scattering before reaching the exit aperture of the geometry via total internal reflection. The CCPC lens is bonded on the solar cell with the use of optical adhesive, and from the previous study [9], it is stated that the encapsulant spillage will lead to light leakage from the edge of the optical element. To consider the edge/corner leakage due to adhesive spillage, the simulation has been carried out by attaching a layer of adhesive in between CCPC lens and MJSC as shown in Figure 3. The t_{al} represents the total thickness of the adhesive layer while t_{as} is the thickness of the adhesive spillage surrounding the bottom edge of CCPC lens. Both the aforementioned variables are the key parameters to predict the optical losses at the point in which the light rays are entering solar cell from the exit aperture of CCPC lens passing through the optical adhesive.



Figure 3. The adhesive layer is inserted into the model for simulation.

From the aspect of electrical performance, the output current generated from a CCPC module (or CCPC lens + MJSC module assembly) can be estimated from its spectral response to the light source. The output current of MJSC module with CCPC lens ($I_{CCPC+MJSC}$), output current of MJSC module without a CCPC lens (I_{MJSC}) and concentration ratio (CR) of CCPC module are determined as follows:

$$\mathrm{CR} = \frac{I_{CCPC+MJSC}}{I_{MJSC}} = \frac{A_{active}\times\frac{q\lambda}{hc}\int \phi_{EQE}(\lambda)\cdot\phi_{Spec(CCPC+MJSC)}(\lambda)\mathrm{d}\lambda}{A_{active}\times\frac{q\lambda}{hc}\int \phi_{EQE}(\lambda)\cdot\phi_{Spec(MJSC)}(\lambda)\mathrm{d}\lambda} = \frac{\int \phi_{Spec(CCPC+MJSC)}(\lambda)\mathrm{d}\lambda}{\int \phi_{Spec(MJSC)}(\lambda)\mathrm{d}\lambda} \quad (1)$$

where A_{acitve} is the active area of MJSC, q represents the electric charge, c stands for the speed of light in vacuum, h is the Planck's constant, $\varphi_{EQE}(\lambda)$ is the external quantum efficiency of each subcell in the MJSC in which it is represented in a function of wavelength, λ, $\varphi_{Spec(CCPC+MJSC)}(\lambda)$ and $\varphi_{Spec(MJSC)}(\lambda)$ are the spectral irradiance received by the MJSC module with and without a CCPC lens, respectively.

To validate the simulated result, an indoor experiment has been carried out by using the Oriel's Sol1A™ Class ABB Solar Simulator. The spectrum of the light source is first measured using a spectrometer so that the value can be used to calculate the output current of the MJSC in the ray-tracing simulation. To ensure both MJSC module without a lens and CCPC module receive the same amount of incident light within the same acceptance angle, the entrance aperture is fixed at the same height with a fixed position. The outcome has been tabulated based on an average of five measurements, and this will be further discussed in the next section.

4. Result and discussion

The optical efficiency profile of CCPC module, the ratio of the light received by the MJSC to the light entering the entrance aperture of CCPC lens, as shown in Figure 4 depicts severe optical losses at each edge/corner of the exit aperture of CCPC lens. The optical efficiency at each particular point of the entrance aperture of CCPC lens has been obtained by using the simulation program and was presented in a heat map as shown in Figure 4(a). The real optical losses in the CCPC lens under direct normal irradiance can be observed with naked eyes (see Figure 4(b)). Due to the adhesive spillage, an obvious light can be seen from each edge/corner of the exit aperture of CCPC lens.

Table 1 shows the optical losses determined from the ray-tracing simulation. By defining the refractive index, n corresponding to different wavelengths, absorption coefficient, α and extinction coefficient, k of the surface/materials, the losses which took place at each component level of the CCPC module can be determined. The majority type of the losses is attributed by Fresnel reflection losses as the incident rays travelled through four different mediums (from air → glass → adhesive → MJSC). However, the greatest percentage among all the losses is recognized as the absorption loss of CCPC lens which is made from B270 Schott glass. This indicates that the material's absorption is the main cause of optical losses. However, it is unavoidable in the current stage as the geometry of the CCPC lens is designed to match with the dimension of the receiver. Yet, this can be a hint for future design work to reduce the system losses. In the simulation, t_{as} is assumed as 1 mm and its refractive index, n is 1.38 at 550nm, which explains why the Fresnel losses from CCPC lens to the adhesive is relatively small due to their small difference in refractive index. The absorption of adhesive is neglected as the thickness is too small to affect the outcome. The overall percentage of each loss is calculated in terms of the input power received at the entrance of the CCPC lens. The optical efficiency of the CCPC module is 69.33% after excluding the total percentage losses.

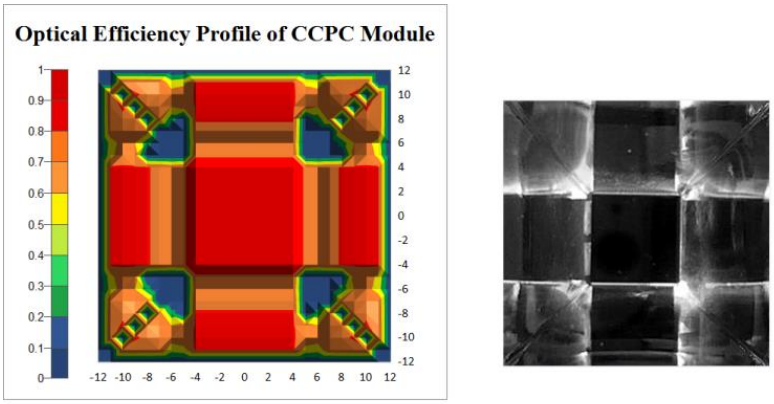


Figure 4. The optical efficiency profile of CCPC module indicates severe optical losses are incurred at the edge/corner under direct normal irradiance. (a) Simulation result. (b) Top view of actual CCPC module.

Table 1. The optical losses at each component level of the CCPC module.

Type of losses	**Percentage (in term of input)**
Fresnel Loss I – From air to CCPC	4.14%
Absorption Loss – CCPC lens (B270 Schott Glass)	11.46%
Edge/Corner Leakage	5.30%
Fresnel Loss II – From CCPC to adhesive	0.20%
Fresnel Loss III – From adhesive to MJSC	9.56%
Total losses	**30.66%**

On the other hand, Table 2 shows the outcome comparison between the simulated and experimental process. The simulated CR is calculated by comparing the output current of the CCPC module to the output current of the MJSC module alone as derived in equation (1). The spectrum of the light source used in the experiment is measured using a spectrometer, and the value obtained is substituted into equation (1) for output current calculation. The simulated result for the output current is slightly lower than the experimental result. There are two possible reasons which causes such outcome: (a) measurement distortion of the spectrometer, (b) the error in the current calculation due to the discrepancy in external quantum efficiency (EQE) of the MJSC provided in the datasheet.However, the result shows that both outcomes are tally to each other with a minor difference of 1.7% when normalized it to CR. From the result, it shows that the CCPC module (CCPC lens + MJSC module) has an overall effective efficiency of 76.17% (4.57 out of GCR of 6.00), which both optical and electrical losses are included with the consideration of current mismatch losses.

Table 2. The outcome comparison between the simulation and experiment.

Type of model	**Calculated Current (I_{SC})**	**Measured Current (I_{SC})**
CCPC lens + MJSC module	34.19mA	43.26mA
Only MJSC module	7.36mA	9.46mA
Concentration Ratio (CR)	**4.65**	**4.57**

In the previous work done by Chong et al. [6], a $CR_{measured}$ of 4.07 is obtained through an outdoor experiment setup. This result is below the expectation as compared to the outcome obtained from this paper. This might be caused by the inconsistent ambient condition applied to the two modules during the experiment. Therefore, the following step in this study is to conduct another outdoor experiment with a more precise setup with the consideration of the same amount of input incidence and acceptance angle for both models.

5. Conclusion

This paper has presented the investigation on the optical and electrical performance of the CCPC module for the application of UHCPV system for both simulation and experimental approach. By considering all the possible losses in the simulation, the CCPC lens has an optical efficiency of 69.33%. For the concentration ratio, the simulation result is 4.65 while the experimental result is 4.57. This indicates that the real CCPC module has an effective optical efficiency of 76.17% since the geometrical concentration ratio of the CCPC lens is 6.00. The absorption loss of CCPC lens and Fresnel reflection losses from the optical adhesive to MJSC interface are the major losses in the CCPC module. The comparison between the simulated and experimental results show a reliable accuracy of the ray-tracing technique used in this study, where two results are tally to each other with a minor difference of 1.7%. In a nutshell, the proposed work can provide a better understanding of optical and electrical properties of CCPC module, which are essential for optimizing the performance of UHCPV system. In future, the performance evaluation of the CCPC will be further studied by performing several tests for different angles of incident light in terms of both polarization and azimuth angle, with the integration of NIDC to determine the overall performance of the whole UHCPV system.

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