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Design and Testing of 3D Printed Cross Compound Parabolic Concentrators for LCPV System

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Abstract. Concentrating Photovoltaic (CPV) Systems has the potential to increase the power output and reduce the cost of PV systems. This work demonstrates a successful attempt to fabricate high performance Cross Compound Parabolic Concentrator (CCPC) using 3D printing. The performance of the 3D printed CCPCs was characterized using a testing setup that consists of a monocrystalline silicon solar cell (10mm x 10mm) mounted on a cooling/rotation stage. Five CCPCs of varied concentration ratio (2.9x, 4.0x, 6.0x, 7.8x and 9.0x) were fabricated and their performance were evaluated. The results show that the optical efficiency of these 3D printed CCPC ranges from 82% to 89%, representing the highest values reported to date. In addition, the angular responses of the concentrators were also evaluated.

INTRODUCTION

One of the biggest challenges that the world faces is to eliminate the dependence on fossil fuels. Renewable energy resources are a promising solution to overcome this challenge. Urbanization, modernization and the increase in human population are the key factors which lead to a sharp increase in the world energy demand [1]. Solar energy is an abundant energy source which provides 120 petajoules of energy per second to the earth. This energy can be harvested to produce electricity or heat (or both) in two main ways, photovoltaic (PV) and solar thermal collectors, however, harvesting this energy efficiently and cost-effectively is challenging [2, 3].

Concentrating photovoltaic (CPV) systems could play an important role as it has the potential to reduce the size of solar cells needed by operating them more efficiently. Using efficient concentrating optics to concentrate the light onto small-area solar cell is considered as one of the essentials for developing the CPVs [3, 4]. These solar optics are divided into two categories according to the physical nature of how the light being concentrating by either refraction or reflection. Refractive concentrators use the lens whereas reflective concentrators use mirrors, both methods aim to capture and concentrate the sunlight to a focal point where the solar cell is placed [3].

Compound Parabolic Concentrators (CPC) are non-imaging optics which allow sunlight collection and concentration onto a receiver (solar cell) for electricity production. The main advantage of a CPC is to allow the incident rays to be collected within an acceptance angle of CPC, while rejecting all the rays outside the acceptance angle [5, 6]. The solar concentration photovoltaics can be separated into three categories: low CPV (1-10x), medium CPV (10-100x) and high CPV (> 100x) [7].

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In this work, Crossed Compound Parabolic Concentrators (CCPC) for LCPV systems were designed and built. The CCPC have been built using a 3D printed acrylic photopolymer material and has applied with a thin-film reflector that used to reflect the sunlight towards the 10mm x10mm Laser Grooved Buried Contact (LGBC) monocrystalline silicon cell [8]. A water-cooling stage was used to maintain the temperature of the solar cell at 25º C. The electrical and optical performance of the CCPCs were investigated by comparing with a non-concentrating system. A comparison of five concentrators at different incidence angles is also presented in this study. All experiments were carried out under standard test conditions (STC), i.e., 1 kW/m^2 at AM1.5G and 25°C.

DESIGN AND FABRICATION OF THE CCPC CONCENTRATOR

CCPC was designed by sweeping four symmetrical parabola profiles to a square cross-section to form a 3D CCPC that has a square entry and square exit to efficiently collect and concentrate the light. The acceptance angle and the height are calculated by using Equations 1 and 2, respectively [9]. The CCPC geometry was designed on SolidWorks CAD software using Rincon et al. [10] equations as shown in FIGURE 1. The CCPC profile reflects all the light which hits at any point of the curve (or internal surface) to its focal point, where will be absorbed by a square solar cell placed there. The CAD file was sent to PreForm Formlabs software and printed by 3D Laser Printer. The reason to use this type of 3D printer is because it offers high resolution (as low as 25 microns) and high accuracy. The printer is based on stereolithography technology where the laser is used to cure the resin and build the concentrator geometry layer by layer. The stereolithography apparatus (SLA) perform a good surface finish and consider ideal for complex geometries using a low-cost resin. In this work, both clear and black resins were used to fabricate the concentrators.

$$\sin\theta_c = \frac{1}{C_g} \tag{1}$$

$$H = \frac{a(1+\sin\theta_c)}{2\tan\theta_c} \tag{2}$$

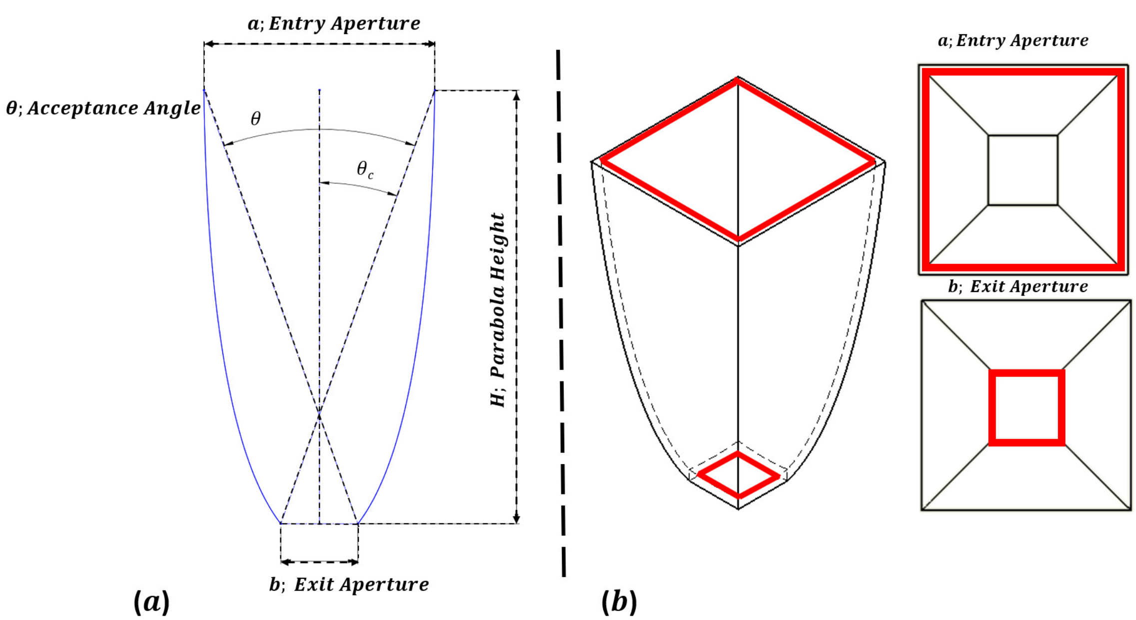

FIGURE 1. CCPC CAD Drawing, (a) 2D CCPC Profile, (b) 3D CCPC Profile.

where; θ_c is the half acceptance angle, C_g is the geometrical concentration ratio, H is the height, and *a* is the entry aperture area.

A chemical treatment was carried immediately after printing the CCPC sample; by immersing and shaking the sample in Isopropyl Alcohol (IPA) bath for 2 minutes, and the sample soaked for 10 minutes in the bath to remove the contamination parts that happened during the printing process. The printed prototype left to dry for about 1 hour before to be ready for the next stage. Five CCPC prototypes were successfully printed; 2.9x, 4.0x, 6.0x, 7.8x and 9.0x of geometrical concentration ratios, where the acceptance angles are being 36º, 30º, 25º, 21 º and 19º, respectively.

A 0.3mm thickness aluminum sheet supplied by *alanod GmbH* [11], with 95% of spectral reflectivity was cut into four segments and applied by hand to fit on the inner surfaces of the CCPC. A monocrystalline silicon solar cell with an effective cell area of 10mm x 10mm was used in the tests. A base at bottom part was added to the CCPC design to hold the concentrator and fix it above the solar cell and the rotary stage that mentioned in the experimental setup section.

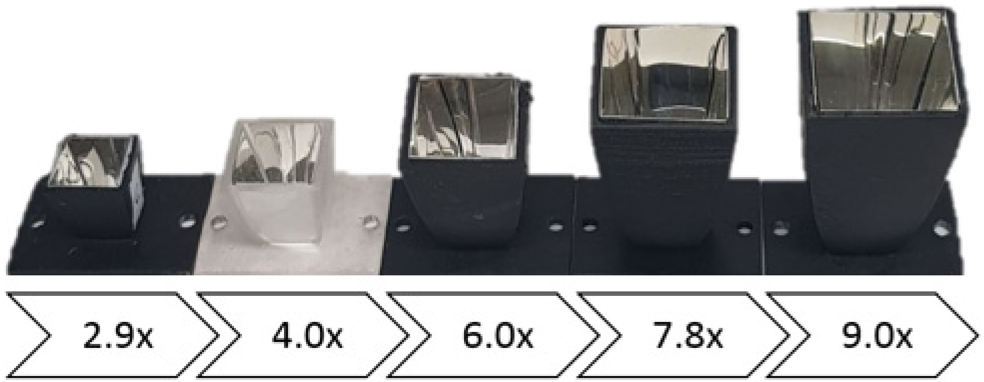

FIGURE 2. Five different CCPC prototypes covered with an aluminum thin-film reflective sheet.

SIMULATION WORK

The optical behavior of the CCPCs was simulated using a ray-tracing software (TracePro) and the optical efficiencies and the irradiance maps were determined prior to the experiments. TracePro was chosen because it has widely been used for developing solar concentrators where the simulation showed a good agreement between their experiments and simulations [12, 13].

In this work, the simulation was essential as it provided a good indication of the CCPCs optical performance. A 4.0x CCPC presented as an example in this paper, while the other CCPCs 2.9x, 6.0x, 7.8x and 9.0x were also designed in the same way. All results are presented and discussed in the results and discussion section.

EXPERIMENTAL SETUP

The experiments were carried out in an indoor environment. Orial Solar Simulator LCS-100 (Class ABB) was used as a light source conformed to the AM.1.5G filter. The simulator was located inside a Faraday-cage to shield the influence of external electromagnetic field and light. The CCPC was placed under the illumination area of the simulator at one sun irradiance which was measured by using a reference solar cell (Solar Survey). The silicon solar cell terminals were connected to a potentiostat (Metrohm Autolab) to measure I-V curves. The cell was mounted on a direct copper bonded (DCB) board, which allows controlling the temperature of the cell and protecting its terminals. The CCPC and the solar cell were screwed over a water cooling stage existing inside the aluminum rotary stage as shown in FIGURE 3. K-type thermocouples were used to monitor the temperature of the heat exchanger, the solar cell and the ambient temperature inside the Faraday-cage. The rotary stage had dual functionality; to rotate the CCPC system at the field of view 180° degrees with 5° rotating step and to keep the cell temperature at 25° C.

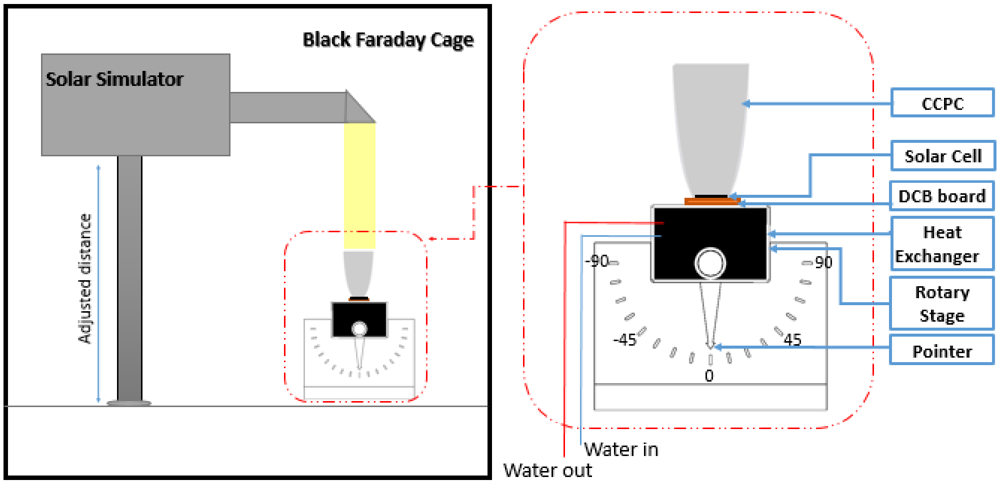

FIGURE 3. Schematic diagram of the experiment setup.

FIGURE 4 shows a photograph of the solar cell mounted on the DCB board coupled to a water cooling /rotary stage before installing the CCPC.

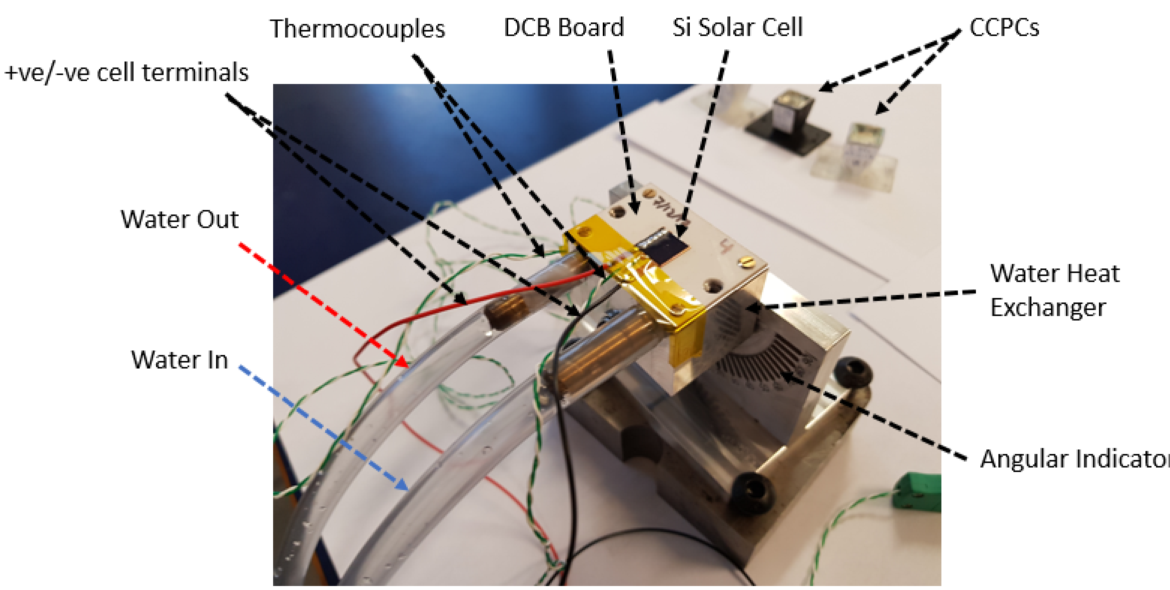

FIGURE 4. A photograph of the cooling/rotary stage system.

RESULTS AND DISCUSSION

The optical efficiencies and the irradiance maps of 4.0x CCPC were simulated by TracePro at two incident angles 0° (normal incident angle) and 30° (acceptance incident angle) respectively as shown in FIGURE 5. The simulation was carried out by using a uniform light with 10,000 incident rays and total irradiance 1000W/m^2. The irradiance map shows the distribution of the direct incident rays and the reflected rays by the CCPC. It gives the optical efficiency of the CCPC through the ratio of absorbed flux by the absorber cell to the emitted flux (light source flux) taking into consideration the geometrical concentration ratio and the reflectivity of the surfaces.

As shown in FIGURE 5 (a), where the light at a normal incident angle using 95% of surface reflectivity, all incident rays were optically reflected to the absorber area. The simulated optical efficiency was 93.13% and the average irradiance over the absorber is 3652 W/m^2. On the other hand, the simulated optical efficiency was only 1.53%, where the CCPC tested at acceptance incident angle and the average irradiance is 60 W/m^2 using the same reflective material.

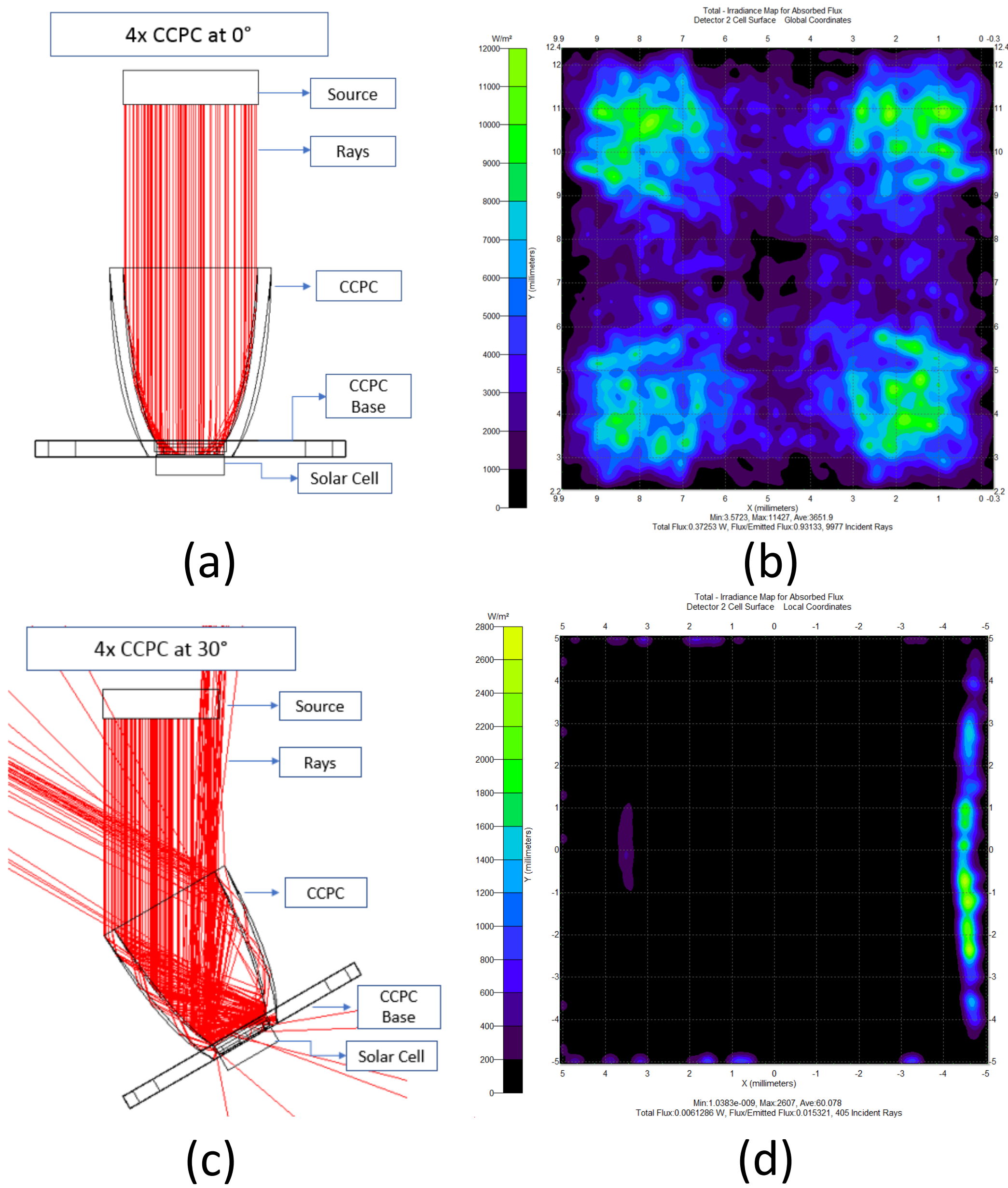

FIGURE 5. (a) TracePro 2D drawing for 4.0x concentrator at 0° incident angle (b) irradiance map at 0° incident angle, (c) TracePro 2D drawing for 4.0x concentrator at 30° incident angle and (d) irradiance map at 30° incident angle.

To validate the simulation, the system was experimentally tested under STC to obtain the I-V curves at both angles of incidents 0° and 30° and thus gives the power curves. The optical efficiencies ($\eta_{Optical}$) of the system were calculated using Equation 3 [14], which give 83.30% for the normal angle and 8.70% for the acceptance angle, respectively.

$$\eta_{Optical} = \frac{I_{SC} with\_concentration}{I_{SC} without\_concentration \times C_g} \times 100 \qquad (3)$$

The 4.0x CCPC presented as an example for this study and the same experimental steps were applied to other CCPCs, 2.9x, 6.0x,7.8x and 9.0x. The simulated and experimental optical efficiency at the normal incidence for all the concentrators was compared and an average of 9% deviation was found. The I-V and P-V curves of the five CCPCs are shown in FIGURE 6.

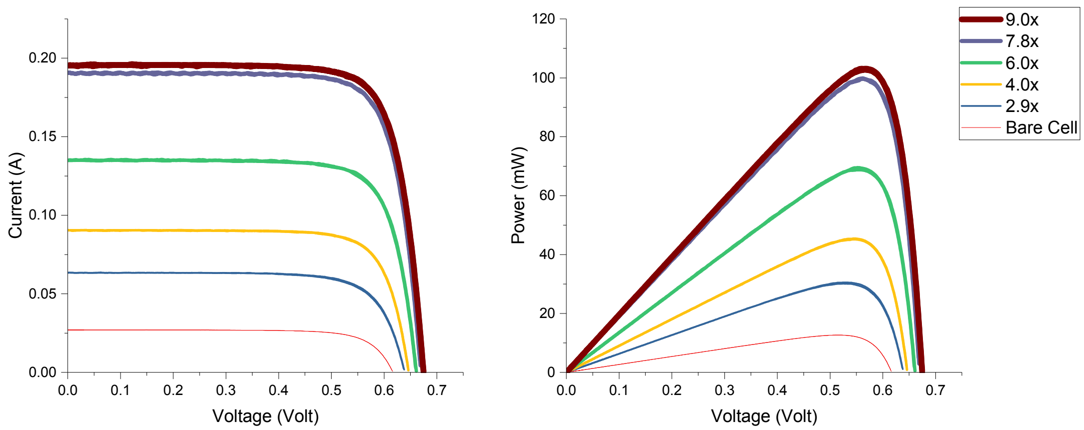

FIGURE 6. I-V and P-V Curves of the CCPCs at a normal incident angle.

The maximum short-circuit current of the solar cell under one sun condition (without the concentrator) is 0.027A. It increased to 0.090A using 4.0x CCPC. FIGURE 6 and Table 1 represent the performance of CCPC prototypes at a normal angle of incidence. It can be seen from FIGURE 6 that the 9.0x CCPC exhibits the concentration ratio among the study prototypes recording an increase in the short-circuit current 3.14 times than the 2.9x CCPC which has the lowest concentration ratio. The fill factor is the ratio of the maximum obtainable power to the product of the open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}). It can be seen clearly from the Table 1, the short-circuit current and the fill factor (FF) increase with increasing the concentration ratio.

TABLE 1. Electrical characteristics of CCPCs.

Concentrator Type Sun (x)	I_{sc} (A)	V_{oc} (V)	Fill Factor (FF) (%)	η (Cell Efficiency) (%)	Power (mW)
Bare Cell	0.027	0.616	75.93	12.78	12.77
2.9x	0.063	0.631	76.85	13.24	30.68
4.0x	0.090	0.644	77.64	13.64	45.00
6.0x	0.136	0.656	77.75	13.97	69.46
7.8x	0.189	0.670	78.53	14.37	99.69
9.0x	0.198	0.675	77.81	14.10	102.50

* Bare cell it is the solar cell tested under one sun irradiance (without concentration).

The angular response of all five CCPCs were also investigated by a varying light incident angle from 0° to ±90° with a step of 5° using the experimental setup shown in Figure 4. The power ratio for the bare cell and the five concentrators were measured and plotted in FIGURE 7.

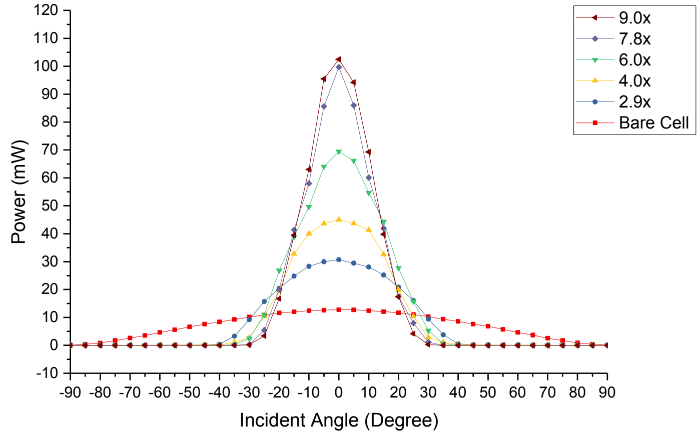

FIGURE 7. The Angular Response of CCPCs

It can be seen from FIGURE 7, the acceptance angle of the CCPCs decreases with increasing the concentration ratio. The concentrators with a higher concentration ratio can collect more amount of power in comparison with low concentration ratio but its required more movements due to its narrow acceptance angle. The 7.8x CCPC has quite similar power output in comparison to 9.0x CCPC; this is due to high optical efficiency which is around 89% and to fewer gaps found at reflector edges.

After investigations, the 7.8x CCPC was originally designed to have a geometrical concentration ratio of 8.0x. In the fabrication process of the CCPC, the concentrator entry aperture has been shrunk from (28.40mmx28.40mm) to (28.00mmx 28.00mm) while the exit aperture and the height remained the same. This made the geometrical concentration to uniformly decrease from 8.0x to 7.8x. This issue has only happened in this concentrator as it left for chemical treatment for a period longer than other CCPCs as we predict. Overall, the unpredictable results of this concentrator subjected to further investigations to study the effects of the geometrical defects on the optical performance.

CONCLUSION

Crossed Compound Parabolic Concentrators for LCPV systems were designed, simulated, built and tested. A comparison of five 3D printed CCPCs was performed and evaluated in an indoor environment. The results showed that the power ratios of CCPCs to the bare cell were 2.40, 3.60, 5.40, 7.80 and 8.00 for 2.9x, 4.0x, 6.0x, 7.8x and 9.0x respectively. Less than 9% deviation between experimental and simulated results was found. The deviation could be attributed to electrical loses due to soldering the solar cell terminals, the misalignment of aluminum reflectors that internally covered the CCPC surfaces and errors of the tracking system. Angular response for five concentrators was investigated at different incidence angles. The power and concentration ratio of the 9.0x CCPC was recorded the highest among the other prototypes studied in this work. However, it has the smallest acceptance angle which implies more tracking steps to capture the sunlight along the day

It can be concluded that the five CCPCs have the potential to increase the electrical output compared with the non-concentrating system. Future work will focus on the system design to minimize the addressed errors and carry out outdoor testing to verify the indoor results.

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