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# Indoor Characterization of Genetically Optimized Circular Rotational Square Hyperboloid (GOCRSH) Concentrator

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**Abstract**—This paper evaluates the performance of a genetically optimized circular rotational square hyperboloid (GOCRSH) concentrator for low-concentrating photovoltaic (PV) application. The experimental analysis of 4 types of GOCRSH namely the GOCRSH\_A GOCRSH\_B, GOCRSH\_Crh and GOCRSH\_D, were tested indoor under standard test conditions of 1000 W/m<sup>2</sup>, AM 1.5G and at the temperature of 25 °C. From the indoor experiments, it was found that the prototypes were showing the maximum power point ratio under normal incidence of 2.9x, 2.6x, 3.9x and 2.7x with the GOCRSH\_A GOCRSH\_B, GOCRSH\_Crh and GOCRSH\_D respectively.

**Keywords**— *genetically optimized circular rotational square hyperboloid concentrator, solar photovoltaic, indoor characterization, opto-electronic gain.*

## I. INTRODUCTION

The world is battling the COVID-19 pandemic that has caused a lot of disruptions and the healthcare systems are struggling to cope especially in developing countries. Energy services are vital to inhibiting the pandemic – from electrifying the healthcare facilities, providing the clean water for sanitation to facilitating communications and IT services that link people while keeping social distancing [1]. However, electrical energy access is a problem in sub-Saharan Africa. The statistic shows that approximately only 28% of healthcare facilities have access to reliable electricity, which is very disturbing [1].

Nonetheless, these sub-Saharan countries are blessed with untapped solar energy has the potential to power these healthcare facilities [2], [3], through the use of solar photovoltaic (PV) system. Although there is declining cost of solar PV around the globe, the cost is still considered expensive especially in developing countries [4]. Silicon-wafer based PV technology accounted for about 95% of the total production in 2017 [5] and their production is very energy intensive leading to

increased greenhouse gas (GHG) emissions [6] and involves the use of toxic substances which have the potential to harm workers and the environment [7], [8]. It has been shown that the this impact on the environment can be lessened by substituting part of the PV material with solar PV concentrators [9]. By focusing light from a large area onto a small area, a solar PV concentrator increases the power output of the PV cell, hence less PV material is required [10]. One of such concentrator designs is the circular rotational square hyperboloid (CRSH) [11].

Recently, the CRSH was optimized using genetic algorithms, and the new design is known as genetically optimized circular rotational square hyperboloid (GOCRSH) concentrator [12]. The optimization allows for several advantages including: (i) a more compact concentrator design; (ii) it is easy to use; (iii) has an optical concentration ratio of around 3x, and wide half-acceptance angles of  $\pm 40^\circ$  which enables it to capture light for more than 5 hours without tracking.

The aim of this paper is to present the characterization of the GOCRSH concentrators indoor under standard test conditions (STC). The chosen concentrators are GOCRSH\_A, GOCRSH\_B, GOCRSH\_Crh and GOCRSH\_D (see Fig. 1). The detailed characteristics of these concentrators are presented in Table I.

The GOCRSH prototypes were CNC machined from transparent polymethyl methacrylate (PMMA) since it is more cost effective for prototyping than injection moulding [13]. The GOCRSH prototypes were machined and hand-polished by Dongguan Bole RP&M Co Ltd. The PV cells were of the laser grooved buried contact (LGBC) type. They were provided by Solar Capture Ltd. These cells are designed for concentrating PV (CPV) applications with concentration ratios below 10x. The measured size of the solar cell size is 100 mm<sup>2</sup> including the area allocated for the front contact. A cell efficiency of only 10% was therefore determined experimentally under STC conditions.

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TABLE I. CHARACTERISTICS OF THE CHOSEN GOCRSH DESIGNS

Lens	GOCRSH_A	GOCRSH_B	GOCRSH_C	GOCRSH_D
Volume $V$ in $\text{mm}^3$	2696	2285	3796	3079
Optical concentration gain $C_{opt \pm 40^\circ}$	2.91	2.75	3.36	3.01
Total height $h_T$ in mm	12.74	11.74	16.64	13.16
Entrance aperture diameter $d_E$ in mm	21.79	20.62	22.01	22.77
Geometrical Concentration gain $C_g$	3.73	3.34	3.80	4.07
Optical efficiency $\eta_{opt \pm 40^\circ}$	0.77	0.81	0.88	0.73

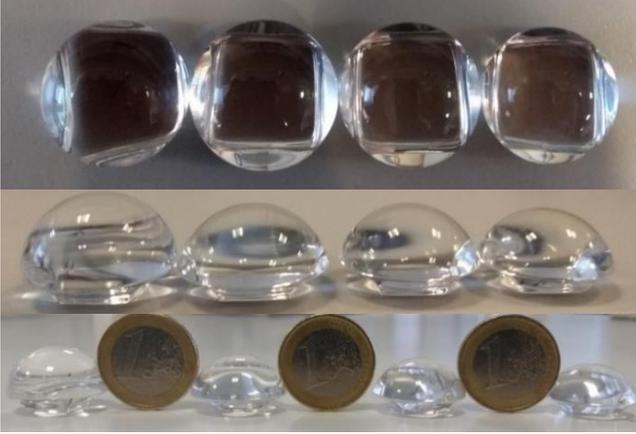


Fig. 1. Prototypes of the GOCRSH\_C<sub>rh</sub>, GOCRSH\_D, GOCRSH\_A and GOCRSH\_B

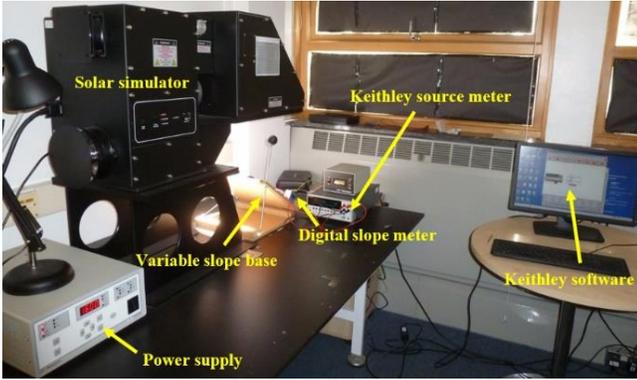


Fig. 2. Indoor experimental setup

The concentrated devices and the reference cell were characterized at normal incidence ( $0^\circ$  inclination), obtaining the current-voltage (I-V) and power-voltage (P-V) curves. Furthermore, the angular response of the concentrators was obtained at the angles of incidence between  $0^\circ$  and  $70^\circ$  at incremental steps of  $5^\circ$ . Mismatches between the simulation results and the experimental results were determined and possible manufacturing errors leading to the mismatch were discussed.

## II. EXPERIMENTAL SETUP

The experimental analysis was carried out indoors under an Oriel® Sol3A™ Class AAA solar simulator. The xenon short arc lamp of an AAA class solar simulator is ozone free and has a spectral performance match between 0.75 to 1.25 times of a 5800 K blackbody. Both the temporal instability and the non-uniformity of the irradiance are lower than 2% within a 200 mm x 200 mm footprint at a working distance of 365 - 395 mm. The

irradiance is adjustable between 0.1 and 1 suns where 1 sun equals to  $1000 \text{ W/m}^2$ . Furthermore, a 1.5 AM filter is integrated to enable STC experimental conditions [14], [15].

The experiment setup is shown in Fig. 2. A SourceMeter instrument from Keithley Instruments (model 2440 5A) was used in combination with the Keithley LabTracer 2.0 software for I-V curve tracing. The SourceMeter is a highly stable multimeter which can function either as a voltage/current source or a voltage/current/resistance meter. The SourceMeter transmits 1700 readings per second and the readings are taken using a four-wire set up which is more accurate than a two-wire set up. The irradiance of the solar simulator was set to  $1000 \text{ W/m}^2$  according to STC and was controlled during the experiment with an Oriel PV Reference Cell System (model 91150V). The reference cell consists of a  $400 \text{ mm}^2$  mono-c-Si solar cell and a type K thermocouple. Thus, the sun irradiance and the cell temperature could be measured simultaneously. When not placed under the solar simulator, the reference cell can be used to measure the room temperature.

## III. RESULTS AND DISCUSSION

### A. Characterisation of the GOCRSH at $0^\circ$ inclination

I-V and P-V curves were traced at  $0^\circ$  inclination to show the difference in short-circuit current  $I_{sc}$ , open-circuit voltage  $V_{oc}$  and maximum power point ( $P_{MPP}$ ) of the GOCRSH concentrator. The I-V curve tracer was set to sweep the voltage from 0.1 V to 1 V to provide the I-V curve of the cell consisting of 100 points. The I-V curves of the concentrated cells and the reference cell are shown in Fig. 3 and the P-V curves in Fig. 4.

Since the measurements were taken at normal incidence ( $0^\circ$  inclination), the difference in  $C_{opt}$  values between GOCRSH\_A, GOCRSH\_B, GOCRSH\_D and the concentrator GOCRSH\_C<sub>rh</sub> is larger than the difference in the averaged  $C_{opt \pm 40^\circ}$  values. The power factor and thus the increase in cell efficiency is as high as 3.9x times for the GOCRSH\_C<sub>rh</sub> and 2.9x, 2.6x and 2.7x for the concentrators GOCRSH\_A, GOCRSH\_B and GOCRSH\_D respectively. The power factor is greater than the  $I_{sc}$  factor since it also includes the logarithmically proportional increase in  $V$  [16].

The  $C_{opt-el}$  of the GOCRSH concentrators at normal incidence ( $0^\circ$  inclination) were calculated and are compared to the  $C_{opt}$  obtained from simulations in Table III. It can be observed that the experimentally determined  $C_{opt-el}$  is distinctively lower than the  $C_{opt}$ , showing an error greater than 10% for the GOCRSH\_A, GOCRSH\_B and GOCRSH\_D and

TABLE II. COMPARISON OF THE SIMULATED  $C_{opt\_0^\circ}$  AND THE EXPERIMENTALLY OBTAINED  $C_{opt-el\_0^\circ}$  AT  $0^\circ$  INCLINATION

	GOCRSH_A	GOCRSH_B	GOCRSH_C <sub>rh</sub>	GOCRSH_D
Optical concentration gain $C_{opt\_0^\circ}$	2.90	2.75	3.39	3.05
Opto-electronic gain $C_{opt-el\_0^\circ}$	2.51	2.40	3.22	2.45
<b>Error in %</b>	<b>13.5</b>	<b>12.7</b>	<b>5.0</b>	<b>16.7</b>

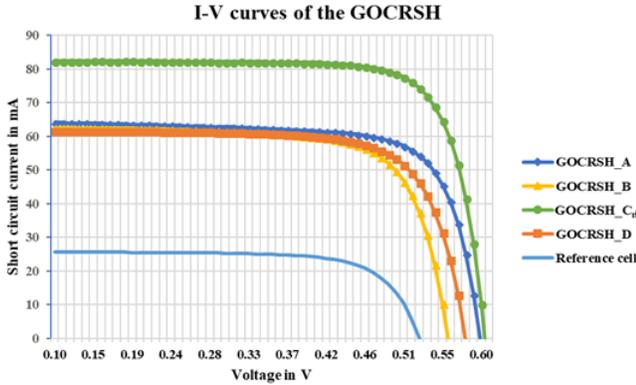


Fig. 3. I-V curves of the GOCRSH under STC conditions at normal incidence

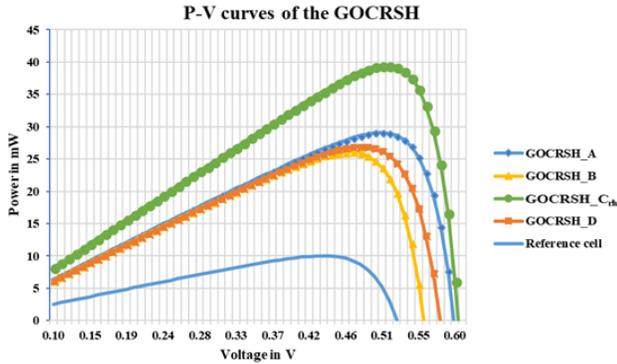


Fig. 4. P-V curves of the GOCRSH under STC conditions at normal incidence

an error smaller than 5% for the GOCRSH\_C<sub>rh</sub>. Before discussing the possible reasons for the obtained errors, the simulated and experimentally obtained angular response are compared in the following section.

### B. Angular response of the GOCRSH

To determine the angular acceptance of the GOCRSH, the I-V curves of the prototypes and the reference cell were measured at angles of incidence between  $0^\circ$  and  $70^\circ$  at incremental steps of  $5^\circ$  and the results were mirrored to represent the angular acceptance as shown in Figs. 5-8. A variable slope was used to tilt the device and the inclination was measured by a digital tilt meter. The irradiance was set to  $1000 \text{ W/m}^2$  and the room temperature was maintained at  $25^\circ \text{ C}$ .

Comparing  $C_{opt\pm 40^\circ}$  and  $C_{opt-el\pm 40^\circ}$ , we can see that there is a high mismatch for the concentrators GOCRSH\_A, GOCRSH\_B and GOCRSH\_D (Table III). While manufacturing errors were expected to lead to a lower  $C_{opt-el\pm 40^\circ}$  compared to  $C_{opt\pm 40^\circ}$ , a mismatch of 9% and greater is not within the expected norm. This is possibly due to prototype manufacturing, device assembly and experiment errors. Since the GOCRSH\_C<sub>rh</sub> has by

far the smallest error between  $C_{opt-el\pm 40^\circ}$  and  $C_{opt\pm 40^\circ}$ , the main error must be due to the reflection caused by the entrapped material on the solar cell. When seen from the top, the bubbles are transparent and show reflective behaviour at certain angles. It is therefore assumed that the reflections are entrapped air bubbles, however, the pattern of the bubbles gives the impression of a brushed liquid. In fact, the primer on the GOCRSH\_A, GOCRSH\_B and GOCRSH\_D cells was left to dry longer than on the GOCRSH\_C<sub>rh</sub>. The primer left to dry too long might have caused the impurities on the GOCRSH\_A, GOCRSH\_B and GOCRSH\_D cells.

A further source of errors is the tilt of the concentrator on the solar cell. This is due to the tabbing wire being positioned on the front and the back contact of the cell at the same cell side. Thus, on one side of the cell, the position of the concentrator is 0.2 - 0.3 mm higher than on the other side. Furthermore, a misalignment of the concentrators on the solar cells leads to ray

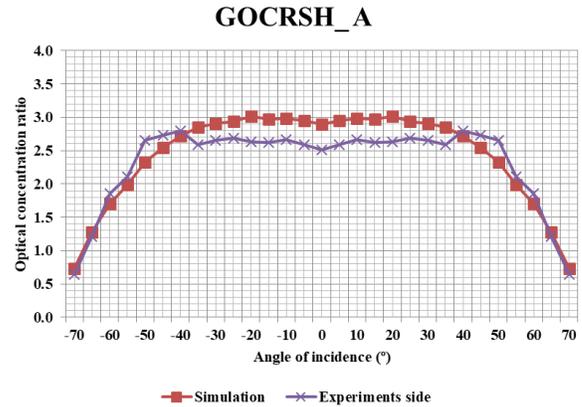


Fig. 5. Experimental and simulated angular acceptance of the GOCRSH\_A

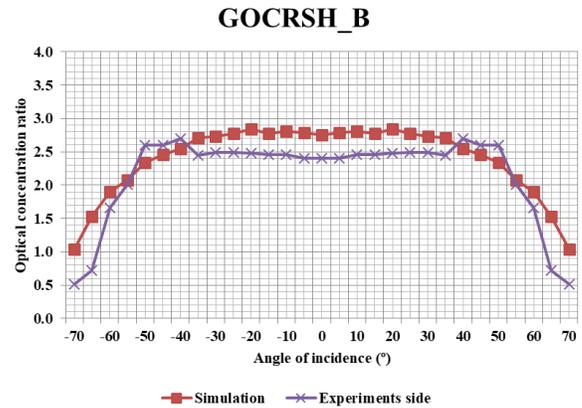


Fig. 6. Experimental and simulated angular acceptance of the GOCRSH\_B

TABLE III. COMPARISON OF THE SIMULATION AND EXPERIMENTAL RESULTS

	GOCRSH_A	GOCRSH_B	GOCRSH_C <sub>rh</sub>	GOCRSH_D
Optical concentration gain $C_{opt\pm 40^\circ}$	2.91	2.75	3.21	3.01
Opto-electronic gain $C_{opt-el\pm 40^\circ}$ tabbing wire on the side	2.64	2.48	3.12	2.55
<b>Error in %</b>	<b>9.28</b>	<b>9.82</b>	<b>2.80</b>	<b>15.28</b>

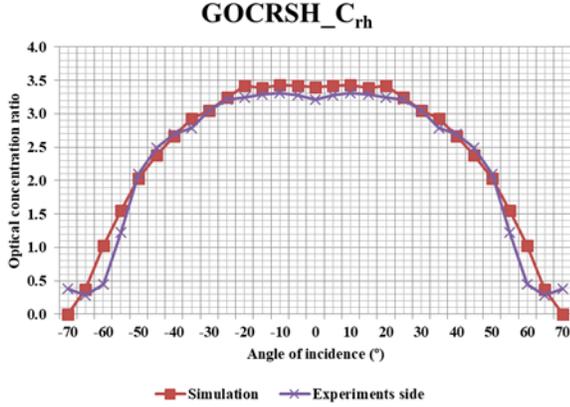


Fig. 7. Experimental and simulated angular acceptance of the GOCRSH\_C<sub>rh</sub>

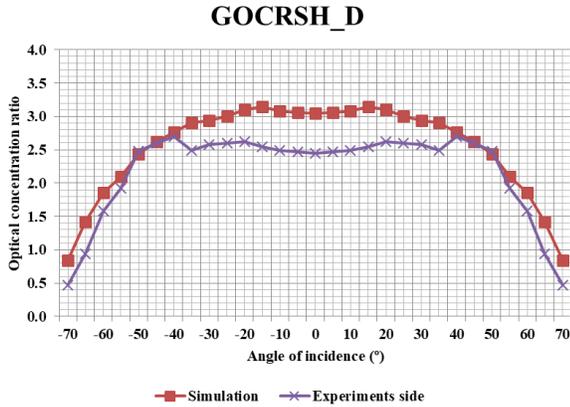


Fig. 8. Experimental and simulated angular acceptance of the GOCRSH\_D

losses. While a slight misalignment can be seen with the GOCRSH\_C<sub>rh</sub>, less visible misalignments of the other concentrators are possible. Another major source of error is the small size of the active cell area which is smaller than the exit aperture width of the GOCRSH by 10%. Further possible errors include: soldering errors, error in the 3D model created from MATLAB coordinates, error introduced during the CNC machined and polishing of the prototype, positioning error of the device on the variable slope during the experimental analysis, and precision error of the used measuring devices.

#### IV. CONCLUSIONS

In this paper, the experimental analysis of the GOCRSH\_A GOCRSH\_B, GOCRSH\_C<sub>rh</sub> and GOCRSH\_D was carried out. The prototypes were analysed indoors under the solar simulator showing an  $P_{MPP}$  ratio under normal incidence of 2.9x, 2.6x,

3.9x and 2.7x with the GOCRSH\_A GOCRSH\_B, GOCRSH\_C<sub>rh</sub> and GOCRSH\_D respectively.

Compared to the  $C_{opt\ 0^\circ}$  values obtained from simulation analysis, the experimentally determined  $C_{opt-el\ 0^\circ}$  showed a reduced concentration ratio by 13.5%, 12.7%, 5.0% and 16.7% for the GOCRSH\_A GOCRSH\_B, GOCRSH\_C<sub>rh</sub> and GOCRSH\_D respectively. Furthermore, the  $C_{opt-el}$  of the GOCRSH was determined at the angles of incidence between 0° and 70° at incremental steps of 5°. The mismatch between the average  $C_{opt-el\pm 40^\circ}$  and the average  $C_{opt\pm 40^\circ}$  was found to be lower than the mismatch between the  $C_{opt\ 0^\circ}$  and  $C_{opt-el\ 0^\circ}$  values.

The lower  $C_{opt-el\pm 40^\circ}$  was identified to be due to several integration errors, including reflective air bubbles on the solar cell, a smaller active area of the cell than the exit aperture of the GOCRSH and the tilt of the concentrators on the cell. Since the GOCRSH\_C<sub>rh</sub> showed the smallest error, the main cause for the high mismatch values was assumed to be due to the entrapped air on the solar cells, which have been observed mainly for the GOCRSH\_A GOCRSH\_B and GOCRSH\_D devices.

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