The design and analysis of a vertical receiver LCPV system.

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Abstract

The main concept of CPV is to make use of optical systems to increase the density of irradiance incident upon the solar cells. Operating solar cells under concentrated illumination offers two main advantages. The first is that fewer solar cells are required due to incorporation of an optical system to concentrate incident irradiance from the sun onto reduced area of conventional solar cells. The second advantage is that this increase in the density of irradiance incident upon the solar cells increases the electrical performance of the solar cells. A challenge in CPV is the design and construction of an optical system that creates a uniform illumination profile. The electrical performance of the solar cells are highly dependent on the uniformity of the illumination profile and non-uniform illumination profiles may lead to solar cell mismatch as well as power loss. This paper discusses the design aspects and characterisation of the optical and electrical subsystem of a LCPV concentrator. A LCPV module was designed and constructed with a geometric concentration ratio of 4.6 X. Optical characterisation includes evaluation of the intensity profile obtained by the optical reflector element. An electrical evaluation was also conducted by the use of I-V characteristics obtained under one-sun as well as under concentration.

1. Introduction

Concentrator Photovoltaics (CPV) is one of the technologies that has attracted a renewed interest due to the increased search for the use of non-fossil fuel based sources of energy to mitigate environmentally damaging effects of using fossil fuel for electricity production. CPV modules are a cost effective alternative to flat-plate photovoltaic (PV) modules since they concentrate sunlight onto small efficient solar cells [1].

In low concentration photovoltaics (LCPV), solar cells are subjected to higher irradiance levels than under 1-sun conditions. The electrical output, and hence efficiency of a LCPV module is dependent on the amount of irradiance, temperature and, more importantly, the uniformity of illumination across the solar cells. A situation where one of the above mentioned factors does not exist harmoniously with the rest can lead to degraded performance for the LCPV module.

Three subsystems exist in CPV modules, namely optical, thermal and electrical. This paper discusses the design aspects and characterisation of the optical sub-system as well as electrical sub-system of a LCPV concentrator. By optimising the aperture area of the LCPV concentrator while still maintaining a uniform illumination intensity across the solar cells, the module's electrical performance can be maximised.

Due to geometric and other physical effects, an optical concentrator does not always produce a uniformly illuminated spot on the solar cell. The concentration level is, therefore,

an average of the concentration profile impinging upon the solar cell [2]. It is important that the optical elements in the system create as uniform an illumination profile across the solar receiver as possible. Non uniform illumination from an optical concentrator upon a solar receiver generates a 3 dimensional temperature gradient, which affects the power output of the solar receiver.

2. Conceptual method

The design that was considered in this study makes use of a vertical receiver LCPV design. The initial design was based on the requirement that the aspect ratio of a module, ratio of module height to width, must be low. In addition, the design implemented, uses a faceted parabolic reflector as concentrator element and had to satisfy a certain set of boundary conditions, the main design concept is shown in figure 1 [3][5].
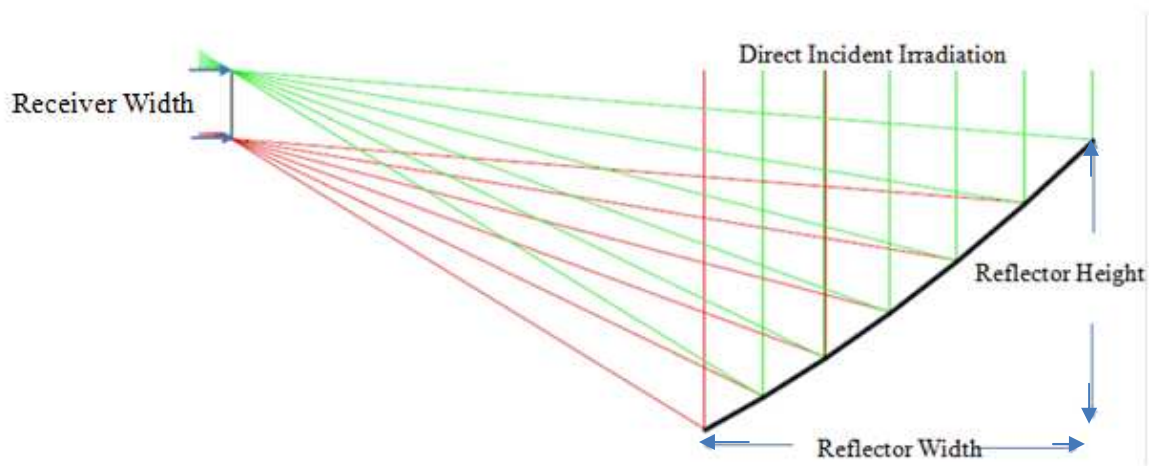

Figure 1: Illustration of LCPV module design.

A suitable mathematical model was developed to design and evaluate various arrangements for the optical elements for LCPV application. This model was based on facetted reflector elements that need to be arranged to meet the set of boundary conditions [3]. From this model an experimental LCPV prototype was constructed. The physical characteristics of the vertical receiver LCPV module prototype are listed in table 1. A photograph of the vertical LCPV prototype can be seen in figure 2 below.

Table 1: Physical aspects of the vertical receiver LCPV module prototype.

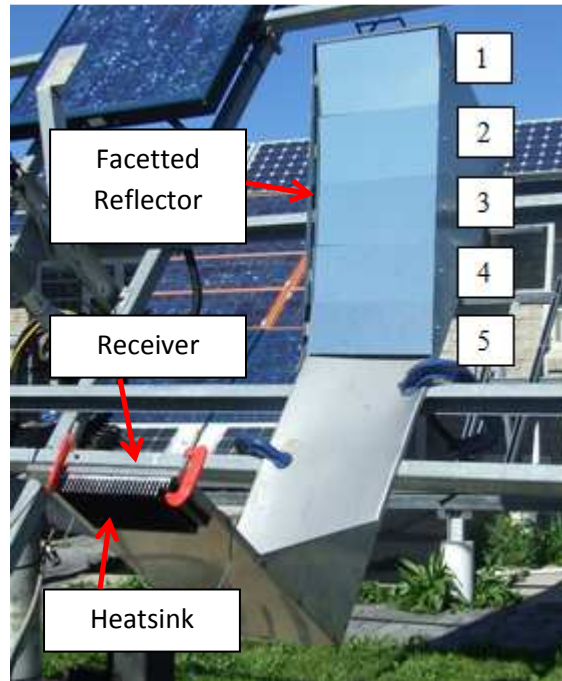| Reflector Width (mm)	461
Reflector Height (mm)	340
Number of facets	5
Receiver width (mm)	100
Geometric concentration	4.6 X

Figure 2: Illustration of constructed prototype.

3. Research methodology

The constructed prototype of this design was optically and electrically characterised. For optical characterisation the intensity profiles were obtained by investigating the contribution of each facet and comparing it to the theoretical contribution. Verification of illumination intensity and uniformity on the receiver plane was done by taking a photograph of the illuminated area and analysing it with a software package named Image J [4].

For electrical characterisation various cell string configurations were tested as receiver for the concentrator system. High current-low voltage receivers were compared to low current-high voltage receivers while keeping the area of cell material constant. Electrical output parameters were measured at one-sun (1000 W/m^2) and under concentration using an Agilent I-V tracer.

4. Results

The illumination profile of the prototype was investigated by digitising a photograph of the illumination profile created from the reflector. The illumination profile created by the reflector can be seen in figure 3.
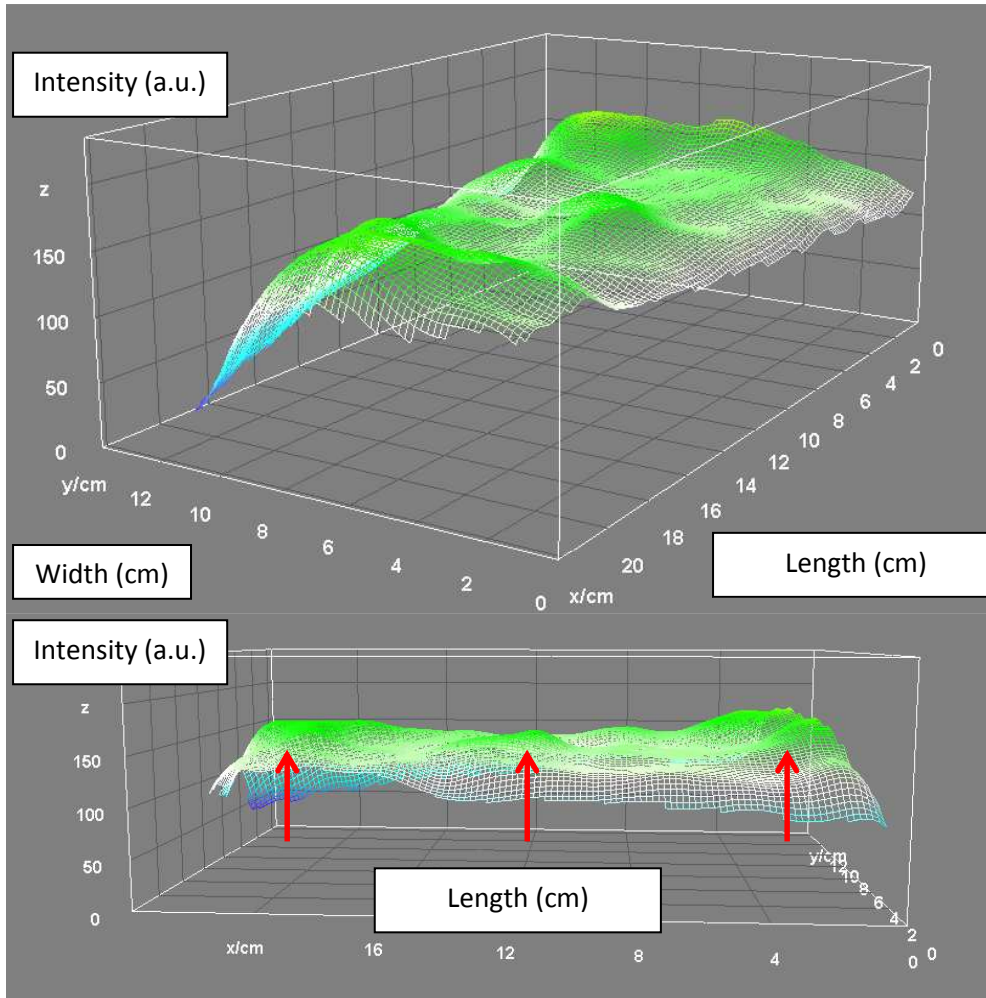
Figure 3: Surface plot of illumination profile obtained from whole reflector element.

Lensing effects are visible in figure 3 from the local high intensity spots, shown in the surface plot, across the illumination profile. The illumination is not ideal and uniform as is required and this will have a definite impact on the electrical performance of the PV receiver. However, the illumination profile obtained for this prototype is more uniform than the illumination profiles obtained from previous constructed prototypes [3] and has a broader high intensity band ('bread' shape) across the length of the receiver area. To further investigate the origin of non-uniformities, the electrical contribution of each facet was investigated. The experimental contribution of each facet and theoretical contribution of each facet is listed in table 2.

Table 2: Theoretical and experimental contributions of each facet.

Facet number	Experimental Concentration (X)	Theoretical Concentration (X)
1	0.84	0.99
2	0.94	0.97
3	0.88	0.93
4	0.81	0.89
5	0.79	0.83
Whole reflector	4.26	4.61

The results illustrate that most experimental contributions of the facets are close to the theoretical contribution of the facets. It is important to note that these theoretical contribution are determined purely from geometrical concentration neglecting optical and reflective losses. Table 2 indicates that the first and fourth facets are the most likely to be the origin of these non-uniformities in the illumination profile of the reflector due to the difference between the experimental and theoretical contribution of each of the facets. The non-uniformities in the illumination profile lead to a decrease in the electrical performance obtained from those facets, due to effects such as cell mismatch.

The purpose of the optical subsystem is to maximise the electrical output from the electrical subsystem. Receivers were created to analyse the LCPV module, these were a 3, 4, 6 and 8 cell string configuration. This experiment was conducted to find the optimal PV receiver for the vertical LCPV module.

The receivers were each tested under one-sun conditions as well as under concentrated illumination. From the I-V characteristics of the 3, 4, 6 and 8 cell string configurations important parameters were obtained and investigated for a comparison to be made between all of these receivers. The I-V characteristics and the electrical parameters of the various PV string configurations can be seen in figures 4, 5, 6 and 7. The I-V characteristics were normalised to standard testing conditions (STC: 1000 W/m^2 and 25 °C).
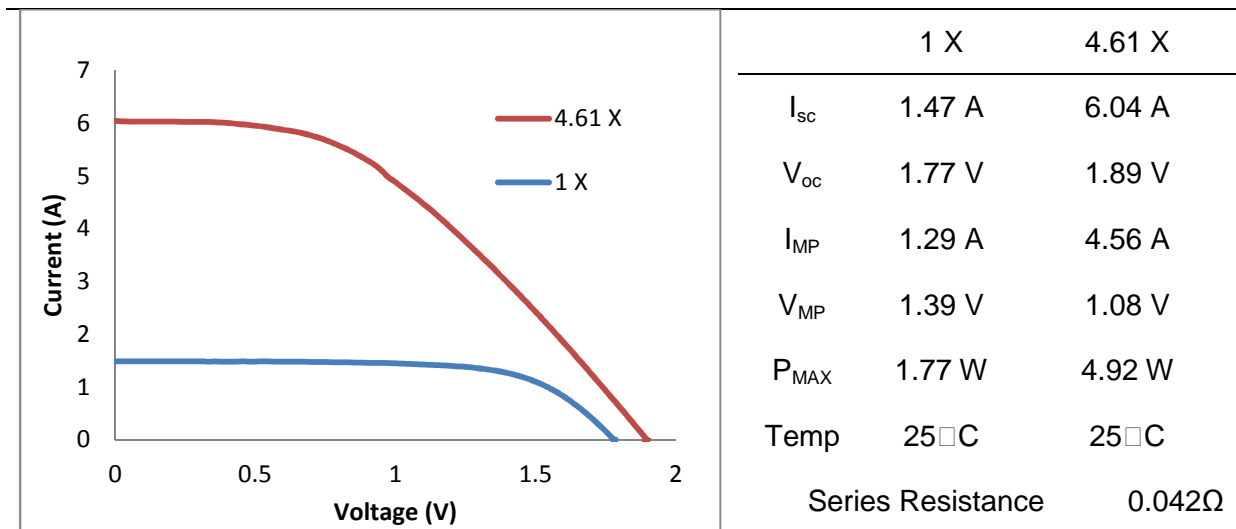

	1 X	4.61 X
I_{sc}	1.47 A	6.04 A
V_{oc}	1.77 V	1.89 V
I_{MP}	1.29 A	4.56 A
V_{MP}	1.39 V	1.08 V
P_{MAX}	1.77 W	4.92 W
Temp	25□C	25□C
Series Resistance		0.042Ω

Figure 4: I-V characteristics of 3 cell string configuration normalized to STC.

	1 X	4.61 X
I_{SC}	1.10 A	4.60 A
V_{oc}	2.42 V	2.58 V
I_{MP}	0.94 A	3.88 A
V_{MP}	1.88 V	1.71 V
P_{MAX}	1.78 W	6.63 W
Temp	25□C	25□C
Series Resistance		0.040Ω
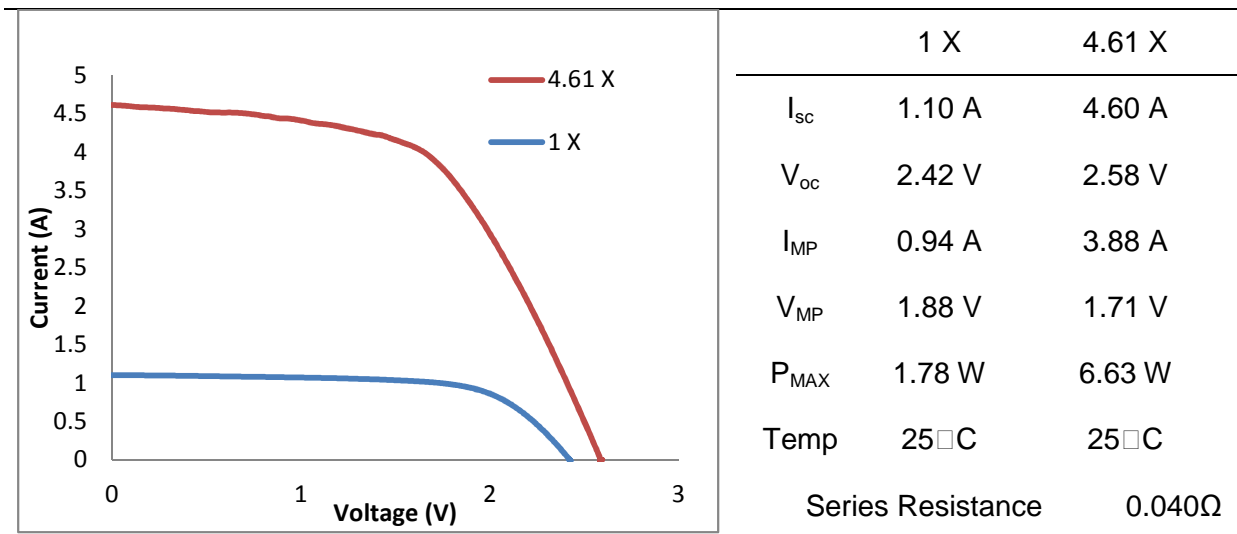
Figure 5: I-V characteristics of 4 cell string configurations normalized to STC.

	1 X	4.61 X
I_{SC}	0.75 A	3.11 A
V_{oc}	3.55 V	3.75 V
I_{MP}	0.65 A	2.75 A
V_{MP}	2.72 V	2.57 V
P_{MAX}	1.78 W	7.09 W
Temp	25□C	25□C
Series Resistance		0.070Ω
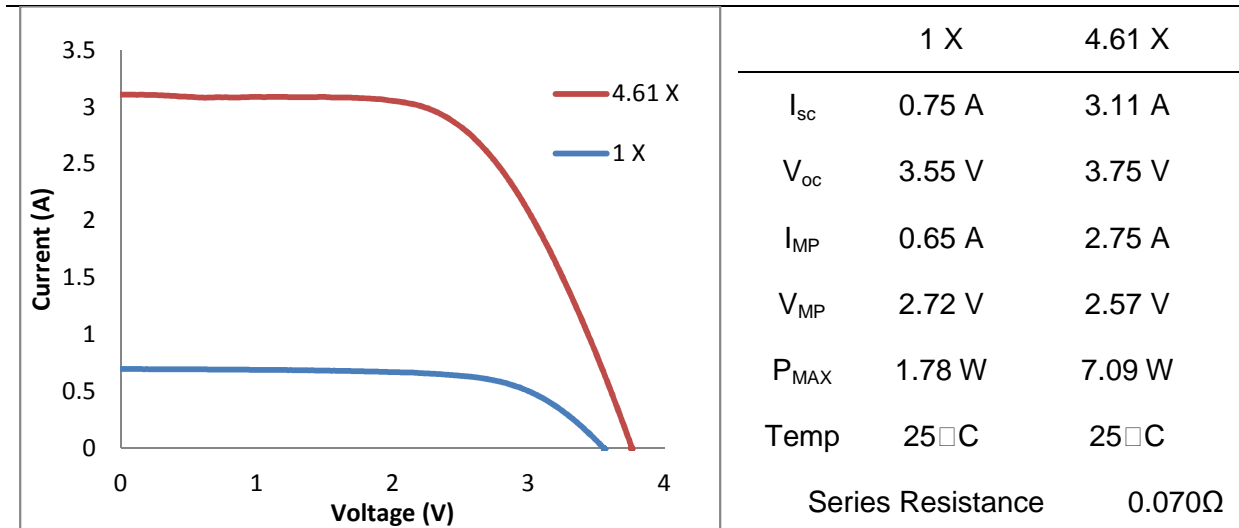
Figure 6: I-V characteristics of 6 cell string configuration normalized to STC.

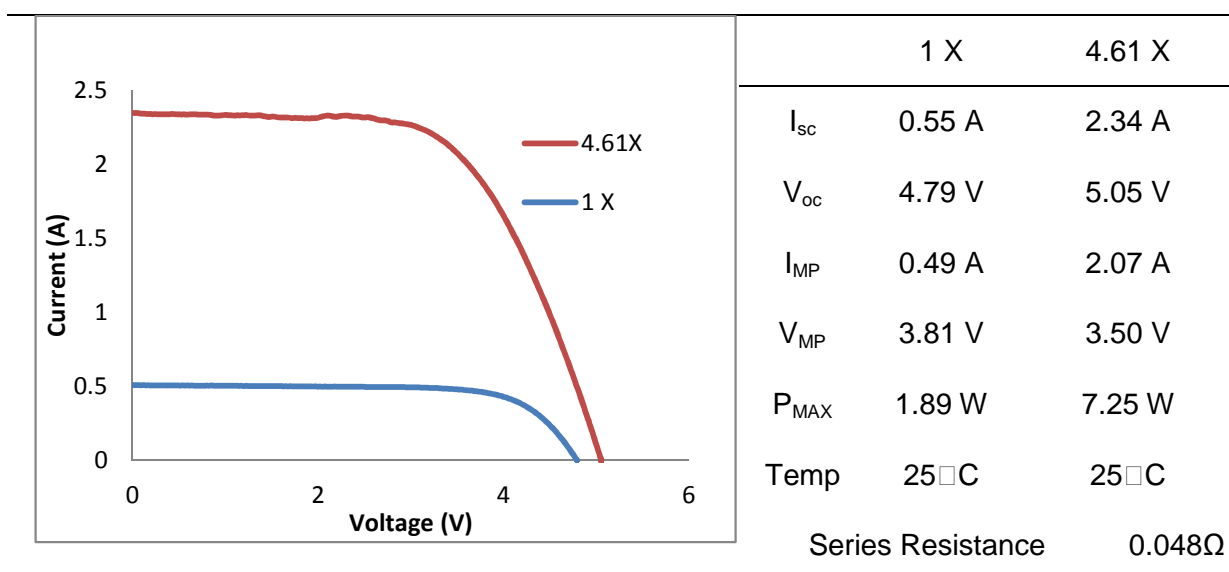|	1 X	4.61 X
I_{sc}	0.55 A	2.34 A
V_{oc}	4.79 V	5.05 V
I_{MP}	0.49 A	2.07 A
V_{MP}	3.81 V	3.50 V
P_{MAX}	1.89 W	7.25 W
Temp	25□C	25□C
Series Resistance		0.048Ω

Figure 7: I-V characteristics of 8 cell string configuration normalized to STC.

Table 3 lists the concentration factors achieved on short-circuit current with each cell string configuration.   Also listed are the series resistance the LCPV receivers extracted from the I-V characteristics.

Table 3: Concentrations obtained for receivers used.

PV receiver	R_S (Ω)	Concentration Factor ($Isc_{(Concentration)}/Isc_{(one-sun)}$)
3	0.042	4.19
4	0.040	4.19
6	0.070	4.20
8	0.048	4.26

A summary of the power and fill factor of each of the various receivers under one-sun as well as under concentrated illumination was also made. Figure 8 illustrates the power figure 9 the fill factor of each receiver as a function of number of cells.
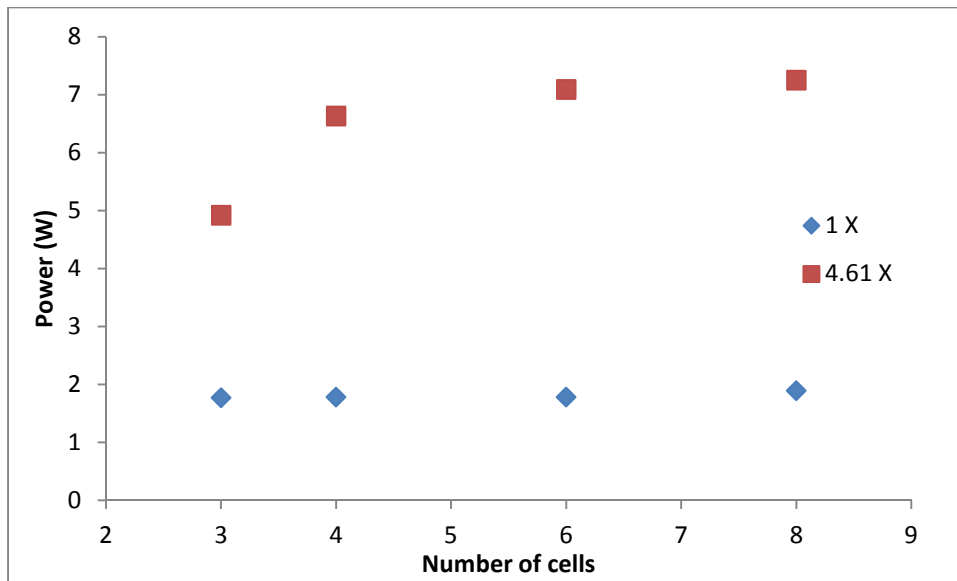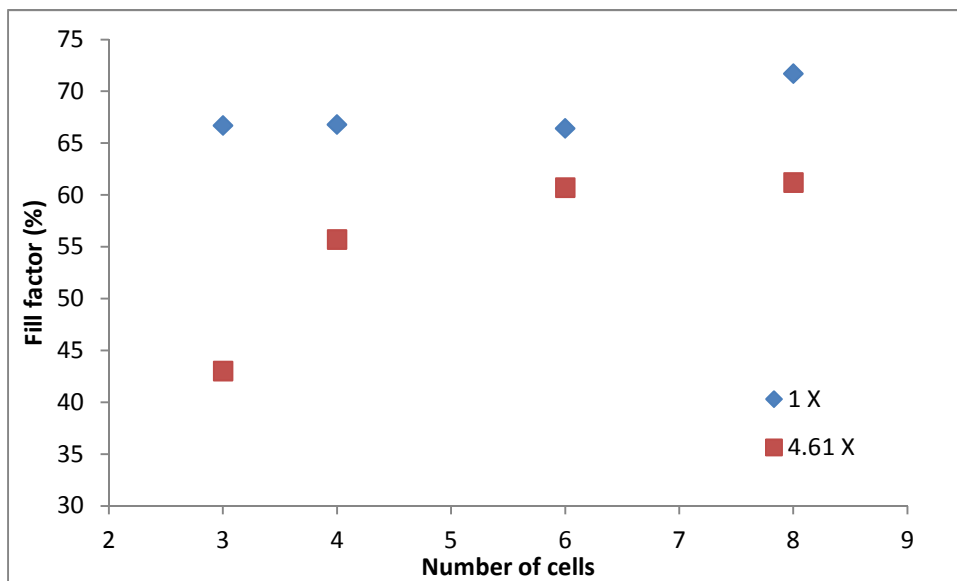
Figure 8: Power vs. number of cells.

Figure 9: Fill factor vs. number of cells.

It is important to remember that the total cell area was kept constant (124.8 cm^2), although the cell sizes were made smaller and the number of cells in series increased. From the I-V characteristics obtained under concentration in figures 4,5,6 and 7 the effect of series resistance is visble on the electrical performance of the receivers. The I-V characteristics have a shrap drop off at the knee leading to a limitation in the maximum power obtained easpecially in the case of the 3 and 4 cell receiver where current levels are high. For the 6 and 8 cell receiver the effect is reduced due to the lower current levels of the receivers. High current levels accompanied by high series resistance in the receiver lead to an increase in the resitive loss term reducing the maximum power obtained from the module This effect is also shown in Figure 8 whichshows that the effect of resistive losses decrease as the current

levels of the receivers decreases, this can be observed from the higher power yields from the receivers as the individual cell size decreases. The 8 cell under one-sun as well as under concentraed illumination yielded a higher power than the other receivers. Figure 9 shows a similar trend when investigating the fill factor values of all the recivers unser one-sun as well as concentrated illumination. The results illustrate that low current-high voltage string configurations (smaller cells) yield a higher power and fill factor under one-sun and under concentration.

5. <u>Conclusions</u>

A vertical receiver LCPV module was constructed from a mathematical and characterised with respect to the optical and electrical subsystem. An optical characterization was done on the LCPV module by investigating the illumination profile of the module as well as contributions of each reflection facet. Optical losses and misalignment of optical elements lead to a reduction in concentration levels and thus performance of the module, causing a reduction from geometrical concentration factor to the operational concentration factor. The optical losses and misalignment of optical elements also cause non-uniformities in the illumination profile of the LCPV module. These non-uniformities in the illumination profile caused by optical misalignments can lead to cell mismatch in the PV receiver, which will cause a decrease in electrical performance of the module.

Various string configurations and cell matching techniques were implemented for the electrical characterization of the LCPV module. Theoretically a geometric concentration factor of 4.61 X was expected, where experimentally 4.26 X was obtained. It is important to note that this theoretical geometrical concentration factor does not account for optical losses of the reflective material. It was found that higher fill factors and maximum power can be obtained by using low current-high voltage cell string configurations when the total PV receiver area is kept constant.

6. <u>References</u>

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