Optical design of a low concentrator photovoltaic module

MA Benecke*, JD Gerber, FJ Vorster and EE van Dyk
Nelson Mandela Metropolitan University
Centre for Renewable and Sustainable Energy Studies

Abstract

This paper reports on the optical design, construction and testing of low concentrator photovoltaic (LCPV) modules. Concentrator photovoltaic (CPV) systems make use of optical elements as well as dual axis tracking to concentrate solar radiation onto a photovoltaic solar receiver. The performance of the concentrator module is highly dependent on the alignment of the optical elements in the system. A mathematical model, based on a predetermined set of boundary conditions, was developed to design and evaluate a suitable optical element configuration for LCPV applications. From this model two new LCPV prototypes were constructed and their performances evaluated by measuring the current-voltage (I-V) characteristics of the photovoltaic receivers. The results show the significance of misalignment as well as the impact of series resistance under concentration.

1. Introduction

In recent times 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), conventional solar cells are subjected to higher irradiance levels. The electrical output, and hence efficiency of a LCPV module is dependent on irradiance, heat dissipation and more importantly the uniformity of illumination across the solar cells. A situation where the above mentioned factors are not optimised can lead to rapid degradation of the laminate materials and a reduction in performance of 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 subsystem of a LCPV concentrator. The integration of these subsystems is very important and in the end will influence the success of the concentrator.

Theoretically an optical concentrator should produce a uniformly illuminated area on the solar cell, but this is not always the case due to misalignment of optical elements as well as non-uniformities on the surface of reflective elements. It is important that the optical elements create a uniform illumination profile across the solar receiver. Non-uniform illumination upon a solar receiver generates a temperature gradient which affects the power output of the solar receiver [2].

Previous research at NMMU resulted in the construction of a V-trough concentrator reaching 2.4 X concentration (geometric concentration $X_G = 3$) [3]. The current study is a continuation of that work, with the aim of improving the concentrator module design. This paper addresses the optical modelling, design and development of a suitable LCPV module, the issues that confront LCPV technology as well as illustrating the feasibility of LCPV technology.

2. Proposed Model or Conceptual Method

The previous research on the V-trough concentrator highlighted several shortcomings of the design. One of the main shortcomings that was identified was the direct correlation between the physical height and the geometric concentration of the module.

The design that was implemented uses a parabolic reflector as concentrator element and had to satisfy the following set of boundary conditions:

i. Module profile must be as flat as possible.
ii. Facetted reflector concentrator.
iii. Receiver (PV laminate) parallel to incident light from sun.
iv. Bottom of receiver in line with top of reflector.
v. Beams incident on opposite ends of facet to be reflected to opposite ends of the receiver.

A mathematical model was constructed in Optica 3 [4] that determines the shape of the concentrator and position of the receiver. The model requires the following variables as input: reflector width, receiver height, angle of receiver with respect to the vertical axis and receiver height above reflector. The model calculates the number of facets, length, position, and angle of each facet. A basic plot of the concentrator layout as well as a theoretical calculation of the concentration ratio (X), taking into account optical losses was obtained. Figure 1 illustrates a basic schematic of the concentrator module indicating incident and reflected rays from the sun.

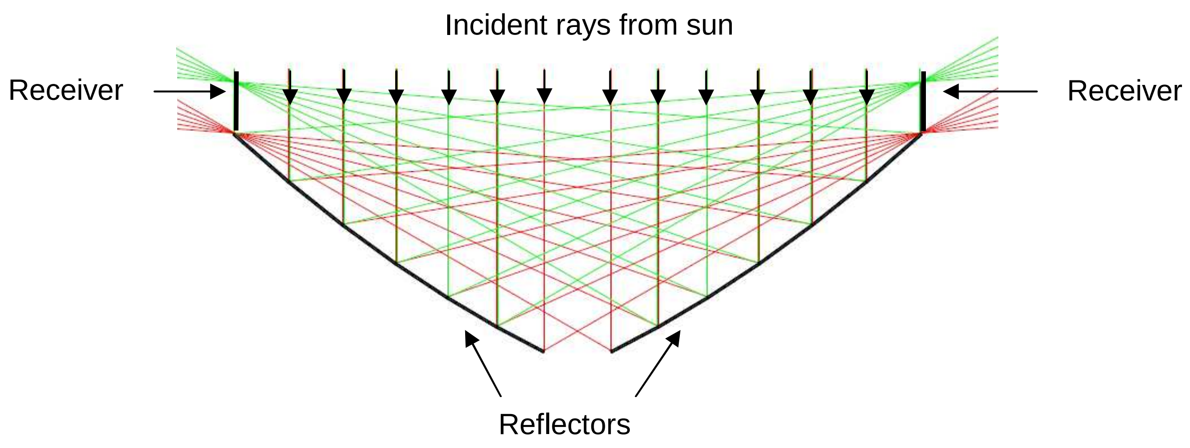

Figure 1: Illustration of optical alignment of concentrator module with ray tracing (green beams indicate top of facet, red beams indicate bottom of each facet, traced in Optica 3 [4])

3. Research Methodology

During this study three LCPV modules were investigated: the previously developed V-trough concentrator [3] and two modules (Module 1 and Module 2) based on the design given by the mathematical model generated using Optica..

Two photovoltaic receiver laminates were used in the characterisation of the concentrator modules; these will be referred to as "receiver laminate 1" and "receiver laminate 2". Receiver laminate 1 comprises of 16 polycrystalline Si cells in two parallel strings, each parallel string consisting of 8 series connected cells. Receiver laminate 2 comprises of three single crystalline Si cells connected in series.

3.1 V-trough concentrator

The V-trough concentrator was mounted onto a dual axis tracker, which tracks the sun throughout the day. Laminate 1 was installed onto the concentrator to obtain a set of I-V characteristics. A one-sun I-V characteristic was also obtained that was used as a reference for comparison.

3.2 Module 1

Module 1 was mounted onto the tracker and I-V characteristics obtained for laminate 1 and laminate 2 separately under solar concentration. Only one side of the parabolic concentrator element was constructed for preliminary testing as shown in Figure 2.

Figure 2: Module 1 installed on a dual axis tracker showing one side of the parabolic concentrator element.

The I-V characteristics of laminate 1 and laminate 2 were also obtained without concentration to be used for comparison. Using this method it is possible to evaluate the efficiency of the LCPV module by means of looking at the effective concentration ratio (*X*) and comparing it to the theoretically calculated concentration obtained from the model.

3.3 Module 2

The second LCPV module, was created in an effort to improve the optical alignment of the first one and was installed on the solar tracker. The optical elements were aligned to obtain the best possible illumination profile on the solar receiver. Laminate 1 was installed in the concentrator and the I-V characteristics were obtained for both no concentration and full concentration. The I-V characteristics obtained from all the LCPV modules were analysed and compared.

4. Results

4.1 V-trough concentrator

In order to analyse the performance of each concentrator the I-V characteristics under concentration as well as no concentration (one-sun) were obtained and compared. Figure 3 shows the one-sun I-V characteristic of receiver laminate 1 as well as the I-V characteristic obtained under concentration, using the V-trough concentrator.

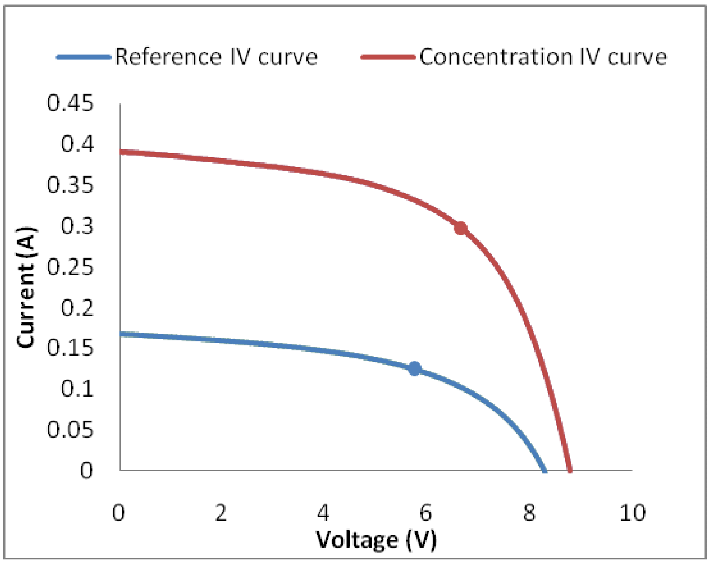

Figure 3: I-V characteristics from laminate 1 using V-trough concentrator (Irradiance: 950 W/m^2).

Table 1: Parameters extracted from I-V characteristics of laminate 1 using V-trough concentrator

Parameter	X= 1	X= 3
I_{sc}	0.16 A	0.39 A
V_{oc}	8.27 V	8.77 V
I_{mpp}	0.12 A	0.30 A
V_{mpp}	5.93 V	6.53 V
P_{max}	0.71 W	1.98 W

Temp	22� C	25� C

Under one-sun (no concentration) conditions receiver laminate 1 illustrated a short circuit current (I_{sc}) = 0.16A, open circuit voltage (V_{oc}) = 8.27 V and a maximum power point (P_{max}) = 0.71 W. Under concentration an increase of these parameters occurred, with I_{sc} = 0.39 A, V_{oc} = 8.77 V and P_{max} = 1.98 W. The increase in I_{sc} yields a concentration ratio of 2.43 X. The concentration with respect to P_{max} yields an increase of 2.78 X. The increase in P_{max} is more than the increase of I_{sc}. This is due to the logarithmic increase of the voltage at maximum power (V_{mpp}) with the increase in solar flux due to concentration.

4.2 Module 1

Figure 4 shows the I-V characteristics obtained from laminate 1 under one-sun as well as under concentration.

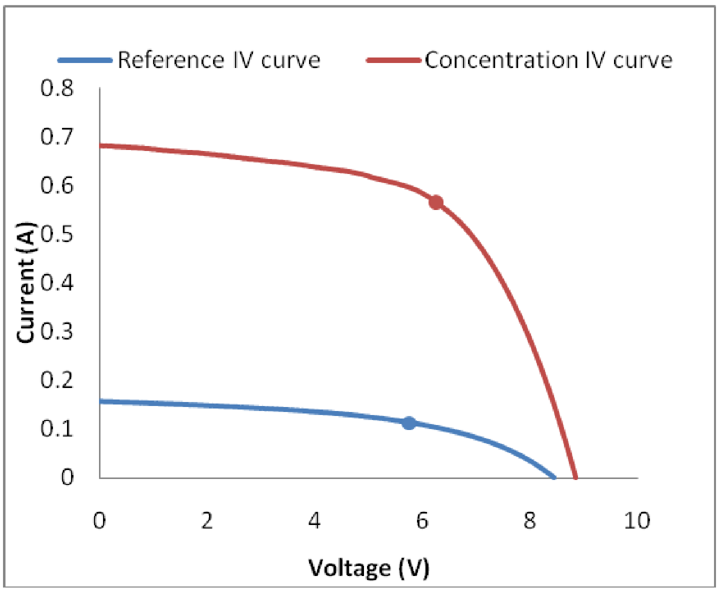

Figure 4: I-V characteristics from laminate 1 using module 1 (Irradiance: 900 W/m^2).

Table 2: Parameters extracted from I-V characteristics of laminate 1 using module 1.

Parameter	**X= 1**	**X= 6**
I_{sc}	0.15 A	0.68 A
V_{oc}	8.43 V	8.83 V
I_{mpp}	0.11 A	0.56 A
V_{mpp}	5.89 V	6.32 V
P_{max}	0.65 W	3.53 W
Temp	23.0□ C	28.3□ C

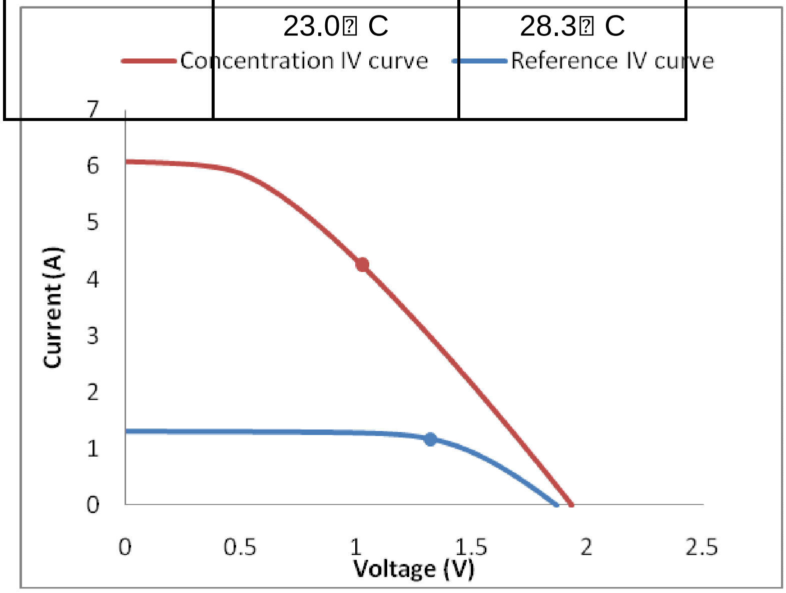

Figure 5: I-V characteristics from laminate 2 using module 1(Irradiance: 900 W/m^2).

Table 3: Parameters extracted from I-V characteristics of laminate 2 using module 1.

Parameters	**X= 1**	**X= 6**
I_{sc}	1.29 A	6.08 A
V_{oc}	1.86 V	1.93 V
I_{mpp}	1.16 A	4.24 A
V_{mpp}	1.32 V	1.02 V
P_{max}	1.53 W	4.34 W
Temp	20.2□ C	26.0□ C

Concentration caused an increase in I_{sc} from 0.15 A to 0.68 A (X = 4.53). The maximum power of laminate 1 increased by 5.4 X, from 0.65 W to 3.53 W. The increase in P_{max} is more than the increase of I_{sc} again due to the logarithmic increase of V_{mpp} with the solar flux.

Theoretically a concentration ratio of X = 6.02 was expected for this design where only X = 4.53 was obtained experimentally. One of the reasons for not reaching this ratio was due to the misalignment of optical elements in the system.

Investigating the results obtained from laminate 2 in Figure 5, one observes that there is a definite change in the shape of the I-V curve. The I_{sc} increased from 1.29 A under one-sun to 6.08 A under concentration. This is a concentration ratio of 4.71 X, which is in the same range that was obtained with laminate 1. The maximum power obtained from laminate 2 increased from 1.53 W under one sun to 4.34 W under concentration, giving a concentration ratio of 2.84 X. This result does not follow the same trend as observed with laminate 1. A basic parameter extraction programme was used to try and explain this effect. The programme requests important I-V parameters and using the one-diode model fits the I-V curve for the module. The one-diode model current–voltage equation is given by:

$$I = I_{ph} - I_0\left(e^{\frac{q(V+IR_s)}{nkT}} - 1\right) - \frac{V+IR_s}{R_{sh}} \qquad [5]$$

Where I_{ph} is the photogenerated current, I_0 is the saturation current of the diode, R_s the series resistance, R_{sh} the shunt resistance and n is the ideality factor.

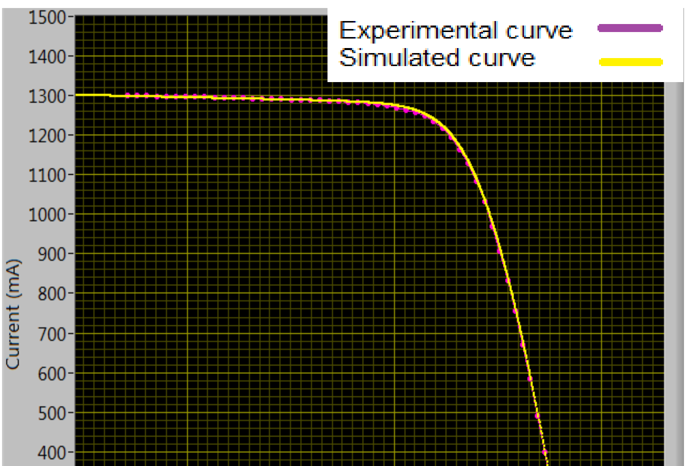

Figure 6(a): Simulation using one diode model of the reference I-V characteristic.

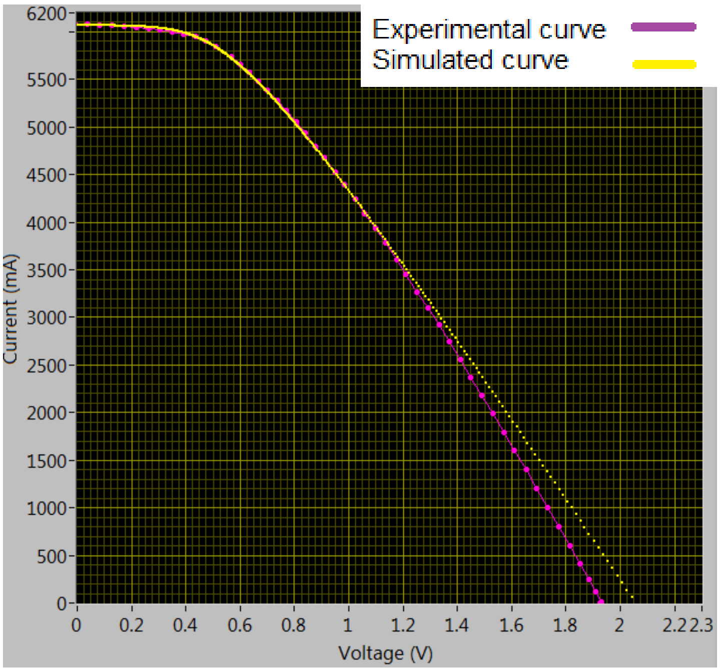

Figure 6(b): Simulation using one diode model of the I-V characteristic under concentration.

From the mode … (b)) it was found that the main reaso … igh series resistance. Under one sun the series resistance does not play a big role, but under concentration when currents reach high levels the effect of series resistance is amplified.

4.3 Module 2

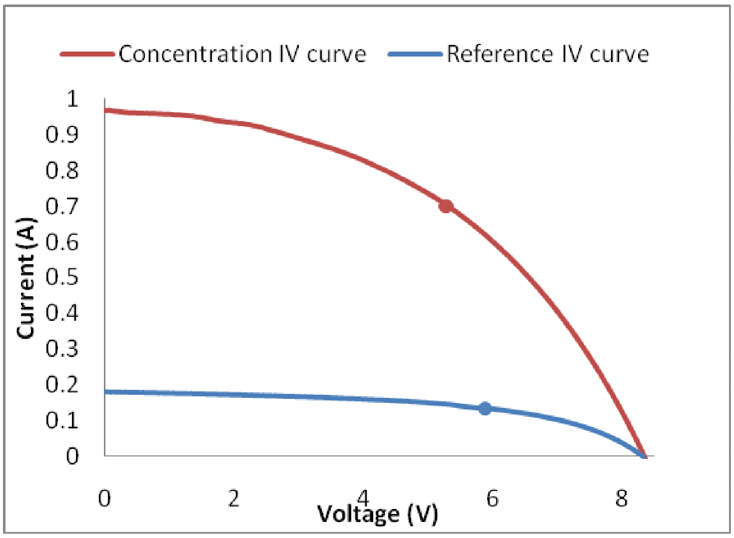

Figure 7: I-V characteristics from laminate 1 using module 2 (Irradiance 934 W/m^2).

Table 4: Parameters extracted from I-V characteristics of laminate 1 using module 2.

Parameter	**X = 1**	**X = 5.8**
I_{sc}	0.18 A	0.97 A
V_{oc}	8.29 V	8.34 V
I_{mpp}	0.13 A	0.69 A
V_{mpp}	5.97 V	5.35 V
P_{max}	0.79 W	3.71 W
Temp	34.3° C	46° C

A few alterations were made to the design of the second prototype. These were; an increase in the parabolic reflector element width, and a 10 mm increase in illuminated area width on the receiver. From the model, a theoretical concentration ratio of 5.8 X was expected. The I-V characteristics showed an increase in I_{sc} from 0.18 A under one sun to 0.97 A under concentration, which when calculated returns an experimental concentration ratio of X = 5.34. Investigating the maximum power obtained from laminate 1, it is observed that it increases from 0.79 W under one sun to 3.71 W under concentration, which yields a concentration ratio of X = 4.7. This increase is less than the increase that was obtained in the short circuit current. The reason for this is that laminate 1 also shows the effects of series resistance under concentration. When the series resistance of laminate 1 was compared to laminate 2 using their I-V characteristics, it was found that laminate 1 has a lower series resistance than laminate 2. One of the reasons for this difference in concentration ratio between maximum power and that of current can be the large difference in temperature of the receiver at the time of the I-V characteristics. The one-sun I-V characteristic was obtained with a receiver temperature of 34°C, while under concentration the receiver's temperature was 46°C. An increase in temperature leads to a decrease in V_{mpp}.

5. Conclusions

The results illustrate the feasibility of the optical design of the LCPV module that can be implemented to improve on the V-trough concentrator design to obtain higher concentrations. It is evident that the optical configuration and alignment plays an important role in determining the performance of a LCPV module. Optical losses and misalignment of optical elements leads to reduction in concentration levels and thus performance. The effects of series resistance were highlighted in LCPV modules as it is one of the main causes of large power losses in receivers under concentration. The results indicate that both module 1 and module 2 improve on the design of the V-trough concentrator from a performance perspective. A higher concentration ratio was obtained without a drastic increase of physical height in the optical concentrator element. The recommended module for potentially achieving the best overall performance is module 2, due to it obtaining a higher concentration ratio (X) than module 1. This resulted from better alignment of the optical elements in the system. The deficiencies in module 1 are a result of the construction of the reflector and did not originate from the design of the LCPV module. As was shown in Table 4 the high temperature that laminate 1 reached under concentration resulted in a decrease in V_{mpp}. This decrease in V_{mpp} resulted in a reduction of the concentration ratio with respect to maximum power. The introduction of a proper thermal management system to laminate 1 would eliminate this reduction of V_{mpp} and result in an increase in maximum power obtained under concentration.

References

[1] A. Luque, S. Hegedus, Handbook of Photovoltaic Science and Engineering, Wiley-VCH, 2003.

[2] A. Luque, V. Andreev, Concentrator Photovoltaics, Springer-Verlag, Berlin Heidelberg, 2007.

[3] B.A. Butler, E.E. van Dyk, F.J. Vorster, Investigation of Low Concentration Photovoltaic Modules and Systems, MSc dissertation, 2010

[4] Wolfram, Mathematica Optica 3.0, http://www.opticasoftware.com/store/index.php , 31/10/2011

[5] T. Markvart, L. Castaner, Practical Handbook of Photovoltaics Fundamentals and Apllications, Elsevier, 2003.