Determining optical performance and current generation of a CPV as a function of intensity distribution

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Abstract. High concentration photovoltaic (CPV) systems utilise non-imaging optics to concentrate and distribute the solar flux uniformly onto a solar receiver to achieve maximum performance and power output from a CPV module. However, in many cases due to mechanical misalignment, tracker error and imperfections in the optical material, the optimum performance of the module is compromised. A LabVIEW programme employing visualization was used to determine the main contributing factor for current generation, i.e. position and intensity of the solar flux distribution. The topography was determined by multiple raster scans of the optical fibre receiver of a spectrometer in the plane of the reflective secondary's aperture where the cell would be placed. The results showed different currents been generated at different points on the cell surface. These results were put into a CPV cell current-voltage (I-V) characteristic simulating algorithm to extract I-V curve at each point. These were then compared with measured I-V curves obtained from the CPV system. The results showed that there was a non-uniform current density (J_{sc}) distribution due to non-uniform spectral and intensity distribution across the cell surface.

1. Introduction

High concentration photovoltaic (HCPV) systems are a cost effective alternative to flat plate photovoltaic (PV) modules in commercial applications. The advantages are the amount of semiconductor material used in a CPV module is significantly reduced and replaced by inexpensive manufactured material like glass, poly(methyl methacrylate) (*PMMA*) and aluminum sheeting. These materials are used to concentrate the solar flux onto the device, which increases the irradiance and thus increases the short circuit current (I_{sc}) of the device.

It is evident that the concentrator systems are dependent on the optical elements to a) collect and concentrate the direct solar flux and b) with the aid of the secondary, distribute the concentrated solar flux uniformly onto the semiconductor device. This will allow for an area of uniform current-generation over the device. The current production is also affected by the optical alignment, tracker error and absorption from the optical materials.
The current production as a function of intensity distribution of the concentrator system was examined using a custom-build scanning mechanism that raster scanned an optical fibre connected to a spectroradiometer in the cell plane. In addition, the current-voltage (I-V) characteristics of various cell and module configurations were measured to determine the resulting current produced by the system and placed in a I-V simulator for analysis.

This paper investigates the current production of a Concentrating Triple-Junction cell (CTJ) as a function of intensity distribution.

2. Theory

To determine the current production of the multi-junction device, one must understand the effect of the spectrum distribution on the subcell material of the device. Since the optical system influences the spectrum and intensity distribution of the light incident on the concentrator cell, characterization of the spectrum is crucial for performance analysis.

A concentrator system generally utilises a substantial portion of direct terrestrial solar radiation (AM1.5D) [1] where the solar spectral distribution is due to the absorption by atmospheric molecules such as ozone, water and carbon dioxide [2].

The optical setup used in this study is based on a module design that is similar to the Sandia Baseline III point-focus Fresnel module [3]. This system utilises a Fresnel lens acting as a primary optical element and a truncated reflective pyramid acting as a secondary optical element, which attempts to distribute light uniformly across the cells' surface. Both optical elements have specific spectral losses due to the absorption and reflection properties of the material.

The Concentrating Triple-Junction (CTJ) solar cells used in this study are devices with a stacked structure consisting of three subcells (InGaP, InGaAs and Ge). The subcells are lattice matched to the Ge substrate and arranged in series from the largest bandgap energy to smallest bandgap energy. The spectral response of the subcells corresponds to wavelength ranges of about 300-700 nm, 500-900 nm and 800-1800 nm, respectively [4]. The resulting short circuit current (I_{sc}) produced by the cell is 13.6 mA at one sun (1000 $W.m^{-2}$) [4].

This arrangement of stacked subcells with increasing bandgaps allows for multiple absorptions of the solar spectrum resulting in a bigger portion of the spectrum to be utilised [5]. In the top subcell, absorption of high energy photons occurs, which correspond to the shorter wavelengths within the solar spectrum. This subcell acts as a filter, absorbing the energy within its bandgap range and transmitting the remaining wavelengths to the second and third subcell where a similar process occurs.

The functionality of the triple junction device is very similar to that of conventional series connected single junction solar cells except that in CTJ cells the subcells are connected via tunneling diodes. Since the triple junction subcells are connected in series, the resulting cell voltage (V_{oc}) is the sum of each of the subcell voltages [3,5]. The short circuit current density (J_{sc}) is more complex than for single junction cells where the current density of a single junction at one sun is given as:

$$J_{sc} = \int S(\lambda)\Phi_{inc}(\lambda)\ d\lambda \qquad (1)$$

where S is the spectral response of the material and Φ_{inc} is the incident solar radiation intensity. In a triple-junction solar cell, where the subcells are series connected, the J_{sc} of the whole device is equal to the smallest photo-generated current density ($Min\{J_i\}$) of a subcell.

$$J_{sc} = Min\{J_i\} \qquad (2)$$

Combining equation 1 and 2

$$J_{scc} = C.Min\left\{\int_{\lambda_{mi}}^{\lambda_{mf}} S(\lambda_m)\Phi_{inc}(\lambda_m)\ d\lambda\right\} \qquad (3)$$

The final produced current density under concentration (J_{scc}) is equal the smallest current density produced by one of the series-connected subcells multiplied by the concentration factor C.

To maximize the current produced by a triple junction cell and to avoid any of the subcells becoming mismatched, and hence reverse biased, all three series stacked subcells must produce the same current.

3. Experimental Procedure

In order to measure the intensity and spectral distribution of the concentrated light that is incident on a triple junction cell, a custom-built X-Y raster scanner programmed in LabVIEW was attached to the concentrator test module with the test cell removed. An optical fibre attached to a spectroradiometer was scanned in the optical plane of the test cell while irradiance intensity and spectral measurements as a function position across the CTJ cell surface were measured. The resulting spectrum at a point as well as the integrated intensity were processed in a Mathematica programme, allowing for visualization of the topographical spectral and intensity distribution across the cell surface. After the completion of the scans, a CTJ cell was placed at the optical aperture of the secondary and current-voltage (I-V) curves were taken for characterization and analysis of the effect of the spectral distribution caused by the optical elements on the CTJ cell. The alignment of the reflective secondary lens was changed to study these effects at a module level.
Spectral measurements were measured at 1X concentration through the Fresnel lens to record the effect on possible current density production.

4.Results and Discussion

Since the spectrum utilised by the concentrator is not standard due to the interaction of the solar flux with the optical material, one must identify and establish where the losses occur.

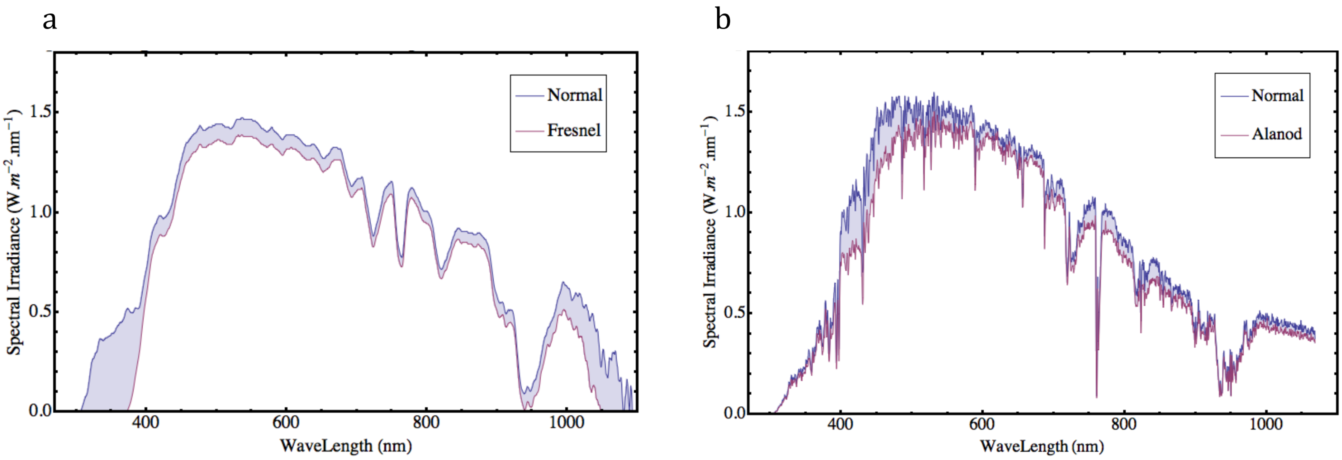

Figure1: Graphs showing the effect of the (a) Fresnel lens and (b) the Alanod material on the spectrum

Figure1 shows the effect on the solar spectrum due to the interaction with the concentrator material. Figure 1a shows that the primary refractive optical material (PMMA)[6] has an affinity to absorb the shorter wavelengths as well the longer wavelengths in the infrared region of the spectrum. The total intensity loss from the Fresnel lens due to spectral absorption amounted to about 10%. Figure 1b shows the reflective losses from the reflective secondary optical material (Alanod Aluminum)[7], with a total intensity loss due to reflection amount to about 5%. The effect on the spectrum is much less and seems be a uniform in the visible and infrared region of the solar spectrum. Whereas slightly less reflection occurs in the UV region of the spectrum where the InGaP is active.

The losses have a much more significant effect on the cell than expected. Equation 1 shows that the current density produced is a function of irradiance and the corresponding spectral response range of that material. Any loss in the spectrum will decrease the current production of the cell. This is the same for flat plate PV, however, a CPV cell has subcells that produce currents independently from each other. They are connected in series and from equation 3 one can see that the subcell, which produces the smallest current, will dictate the current production of the device. The potential current density of each cell was calculated to be 14.33 mA.cm^{-2}, 14.28 mA.cm^{-2} and 19.45 mA.cm^{-2} for the InGaP, InGaAs and Ge, respectively, at 1000 W.m^{-2}.

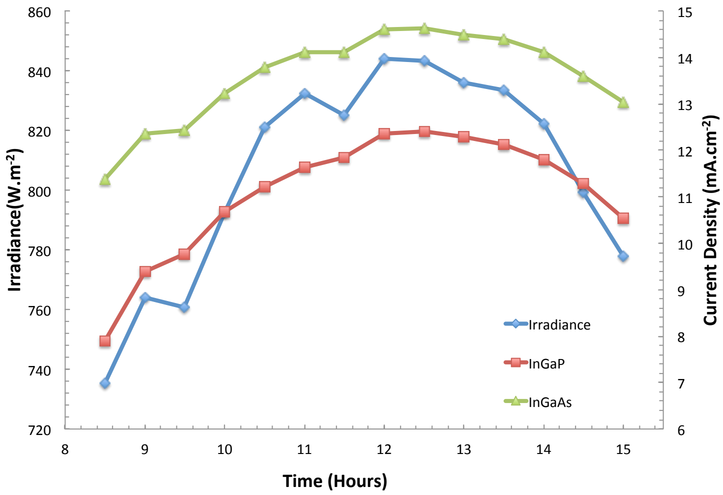

Figure 2: Current density of CTJ subcells at different irradiance measurements.

Figure 2 shows the possible current production of the InGaP and InGaAs subcells at 1X by irradiation through the Fresnel lens material. The theoretical current density values of the subcells are very similar at 1X concentration and since they are irradiance dependent, their increase and/or decrease should be proportional to each other as the device design is optimized to do so. However, the trend shown in figure 2 does not show this. This can be contributed to the fact that the spectrum is not the same throughout the day. Also seen from the figure 2 is that at solar noon there is a difference of about 1 mA.cm^{-2}, which from theory should be relatively the same.

The effect of the absorption of the wavelengths in InGaP region by the optical elements are suspected to be the cause of the decrease in current density as a result of absorption which causes a subcell mismatch. This will decreases the current production of the cell and as the subcells are series connected and will cause mismatch, which could lead to damage of the cell.

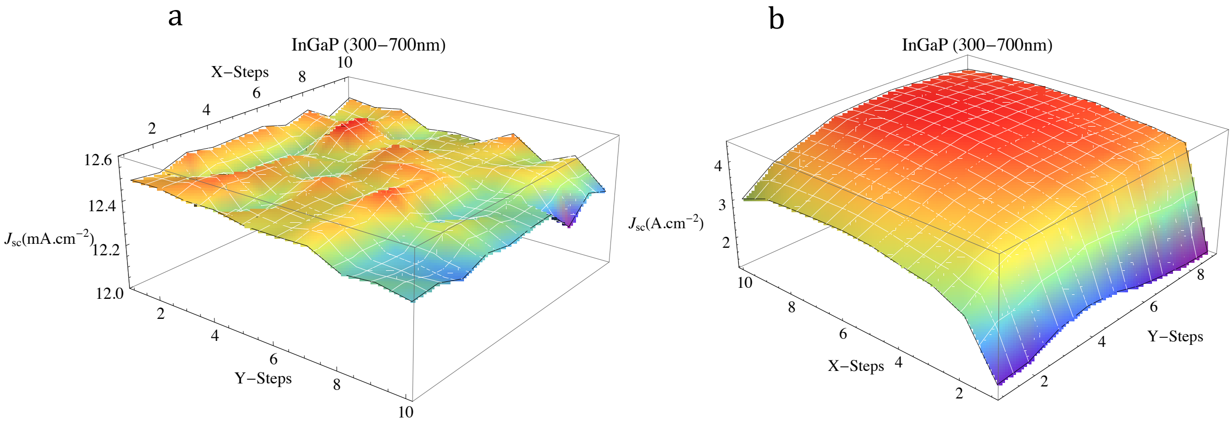

Figure 3: Current density plots of the InGaP subcell as a function of position at a) 1X and b) 330X.

Figure 3 shows the current density potential distribution of the current-limiting InGaP top subcell at 1X and 330X concentration, respectively. In figure 3a, one can see that there is a very slight non-uniform distribution pattern at 1X concentration which leads to a small difference in the current generation potential across the cell's surface. The average direct irradiance at 1X was measured to be 852W.m^{-2}. Figure 3b shows the current density distribution at 330X. This current density distribution is less uniform than at 1X and tapers off drastically on the edges. This shape is due to the distribution of the solar flux produced by the optical elements. The optical elements consist of a primary refractive Fresnel lens and a secondary reflecting truncated pyramid structure. The edges showing regions of low current density correspond to regions of low solar intensity.

The current produced for the whole cell at 1X concentration was 12.5mA at 852W.m^{-2} while the current produced by the cell at 330X concentration was 4.38 A at 864 W.m^{-2}. The total current produced by the cell is the integrated current density distribution over the whole cell area shown in figure 3a and b.

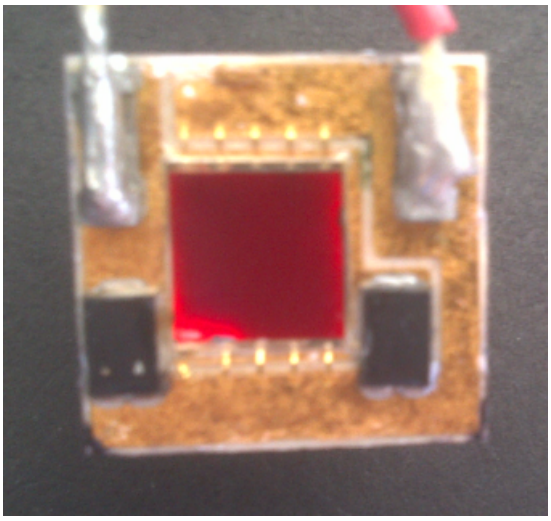

Figure 4: Photograph of CTJ cell that as undergone the describe distribution.

Figure 4 shows the effect on the cell of the current density distribution seen in figure 3b. The cell shown was reverse biased above the V_{oc} of the CTJ cell (2.6V). The bias produced a luminescence pattern in the visible region of the electromagnetic spectrum across the cell. Intense regions of luminescence coincide with areas of high carrier recombination. The intensity of the luminescence pattern seen in figure 4 corresponds well with the current distribution pattern seen in figure 3b. The low luminescence intensity areas shown in figure 4 correspond to regions of low free carrier density in the subcell. It is proposed that a prolonged exposure to a non-uniform high solar flux density may induce damage which leads to deficiencies in the free carrier concentrations of the CTJ device.

5. Conclusion

The results show the effect of the optical performance and current production as a function of the intensity distribution on the performance of a multi-junction solar cell. It is evident that the optical alignment as well as the spectral interaction of the incident solar radiation with the primary refractive and secondary reflective optical material dictates the intensity and spectral distribution of the concentrated solar energy on the CPV cell.

The current density distribution also showed the possible premature failure of the cell due to a non-uniform flux distribution on the cell. To achieve optimum results and performance, the optical system must be carefully designed to allow for the most uniform distribution and least amount of spectral losses. In doing so, one will prevent the occurrence of premature failure from reverse biasing and thus prolonging the lifetime and general performance of the cell as well as the module.

6. References

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