354: Improving illumination and temperature distribution uniformity in high concentrating solar cells

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High concentrating Photovoltaic (HCPV) has the potential to replace the expensive PV material with cheaper optical elements. The use of high solar concentration ratios with the triple junction III-V solar cells offers potential of high solar cell efficiency and power output. However, non-uniformity of the incident flux is detrimental to the CPV technology as this tends to cause hot spots and current mismatch leading to reduced electrical efficiency of the system and degrade the life of the solar cell. In this work, a point focus Fresnel lens was developed and the influence of using a small square reflector placed above the PV surface as a Secondary Optical Element (SOE) in alleviating the non-uniform illumination and temperature distribution was investigated. Also, the SOE height and material reflectivity influence on the optical performance was examined. This was done by implementing optical and thermal simulations using advanced ray tracing method and Multi-physics finite element software respectively. Incident rays distribution uniformity was evaluated using the standard deviation from the mean value. A low standard deviation indicates that most received rays by the solar cell are close to the mean value i.e. more uniform. Results show that a combination of introducing a short SOE (60mm) made from 95% reflective material above the PV and increasing the distance between the PV and the Fresnel lens (l) to 500mm significantly improve the surface illumination uniformity. The achieved uniformity standard deviation is less than 3 with minimum loss in received power i.e. 48.25W in case of introducing SOE and l=500mm compared to 49.07W where receiver placed at focus point.

Keywords: Multi-junction PV, optical efficiency, high concentration, Fresnel lens, non-uniform illumination

1. INTRODUCTION

Global warming, increased fuel prices, worldwide conflict, and increased environmental awareness are major factors of encouraging intensive research and development of renewable energy. Solar energy technologies including solar heating, solar photovoltaic, and solar thermal electricity can contribute solving energy problems in the world (Hoeven 2011: page19). PV is a promising technology which has the advantage of converting sunlight directly into electricity. Solar PV power has been one of the fastest growing renewable energy technologies and it is anticipated that this technology will play a major role in the future of global electricity generation (Twidell & Weir 1986: page182). The new technology, III-V generation multi-junction solar cells, offer high efficiencies exceeding 43% compared to traditional solar cells made of a single layer of semiconductor material (Micheli et al. 2013: page01). The main challenge of promoting PV is the high initial cost when compared to electricity generated from conventional sources (Mah 1998: page02). Concentrated PV systems offer advantages where space and cost are reduced as the expensive PV can be replaced with cheap optical lenses.

A typical CPV system consists of one or more optical element which could be either reflective or refractive (Madhugiri 2012: page1381). The Fresnel lens is a known refractive optical element as a concentrator with many advantages such as compact size, lower weight and material cost (Pan et al. 2011: page4283). The main goal of the concentrators is to increase the concentration ratio (CR). However, concentrators produce high surface temperature as well as non-uniform distribution of illumination on the receiver which can ultimately degrades life of the solar cell (Baig et al. 2012: page5890). A classical method to reduce the non-uniform illumination and improve the uniformity is introducing a SOE to a HCPV (Baig et al. 2012; Benítez et al. 2010; Hernández et al. 2008; Victoria et al. 2013).

In this work, the effect of varying the distance between the receiver and the Fresnel lens (*l*) and inserting SOE above the receiver are examined using ray tracing software. Moreover, the influence of SOE material reflectivity on the optical efficiency was also investigated. Finally, irradiation distribution from this software is imported to COMSOL Multiphysics and thermal simulation is executed to demonstrate the resulted temperature profile on the PV surface.

2. FRESNEL LENS MODELLING

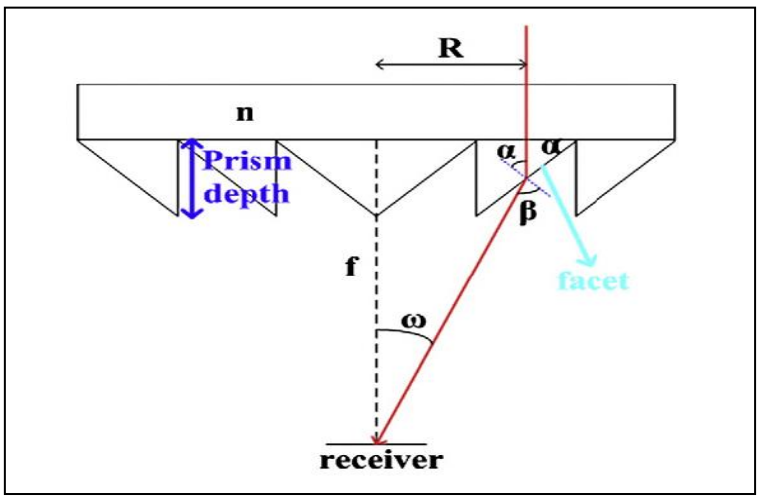

Figure 1: schematic of planar Fresnel lens (Pan et al. 2011)

Figure 1 shows schematic of planar Fresnel lens. Each Fresnel lens consists of serial pitches of Fresnel lens facets. The following equations describe each pitch of the Fresnel lens (Leutz & Suzuki 2001: page67).

$$n \sin \alpha = \sin \beta \quad (1)$$

$$\tan \omega = \frac{R}{f} \quad (2)$$

$$\beta = \alpha + \omega \quad (3)$$

$$\tan \alpha = \frac{R}{n\sqrt{R^2+f^2}-f} \quad (4)$$

Groove pitch of Fresnel lens here is upside down (grooves in) which is suitable for dusty environment as dust can deposit within these grooves and cause shadows on the PV (Leutz & Suzuki 2001: page70). Snell's law is applied on the incident ray as shown in figure 1 where R is the distance between incident ray and the centre axis of the Fresnel lens, n is the refractive index of the Fresnel lens, ω is an angle between the normal of the receiver and the refractive ray, β is an angle between the normal direction of the Fresnel lens's facet and the refractive ray, and *f* is the focal length (Pan et al. 2011: page4285).

In this investigation, the developed Fresnel lens has a focal length (*f*) of 460mm, the Groove pitch of 3 mm, Fresnel lens thickness of 3mm, and F number of 1.3. The modelled Fresnel lens is made from Polymethyl Methacrylate (PMMA) with a refractive index of 1.49. The area of this Fresnel lens and the receiver is 62500 mm^2 and 100 mm^2 respectively resulting in a geometry concentration ratio of 625X where X is the solar radiation received taken as 1000 W/m^2.

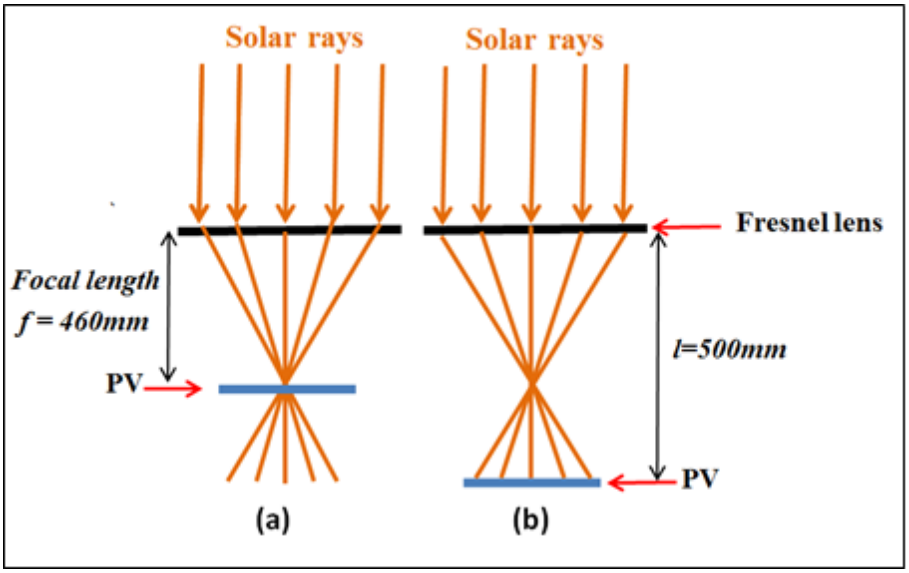

Figure 2: Receiver (Solar cell) at: a) focal point & b) l=500mm

Optical efficiency and illumination uniformity are two important parameters that need to be considered during the development of Fresnel lens. In order to evaluate the optical performance of above Fresnel lens, it is simulated using advanced ray tracing engineering software called Optisworks. Figure 2 shows how the rays are refracted by the groove facet angles of the Fresnel lens to the PV at the focus point and at a distance away from the focus point (l).

3. RESULTS

Incident rays uniformity was evaluated using the standard deviation. A low standard deviation indicates that most received rays by the solar cell are close to the mean value i.e. uniform.

Figure 3 shows the received ray distribution at the surface of the PV cell placed at the focus point (figure 2a). It can be seen that the developed Fresnel lens produces high energy concentration at the centre of the PV cell between -0.5 to +0.5mm region exceeding $55x10^6$ W/m^2. This will create a hot spot on the receiver which can reduce the conversion efficiency due to the current mismatch as well as the reliability of the solar cell.

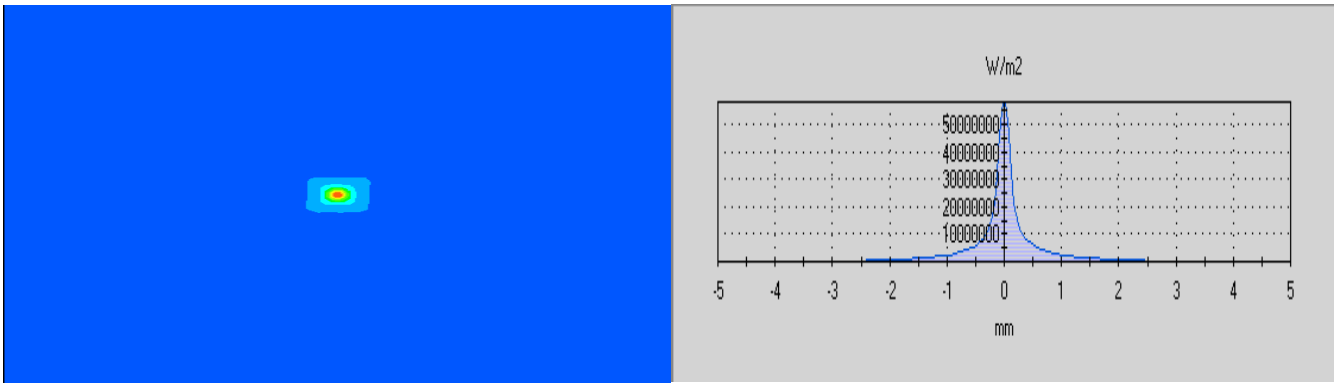

Figure 3: Irradiance distribution on the solar cell

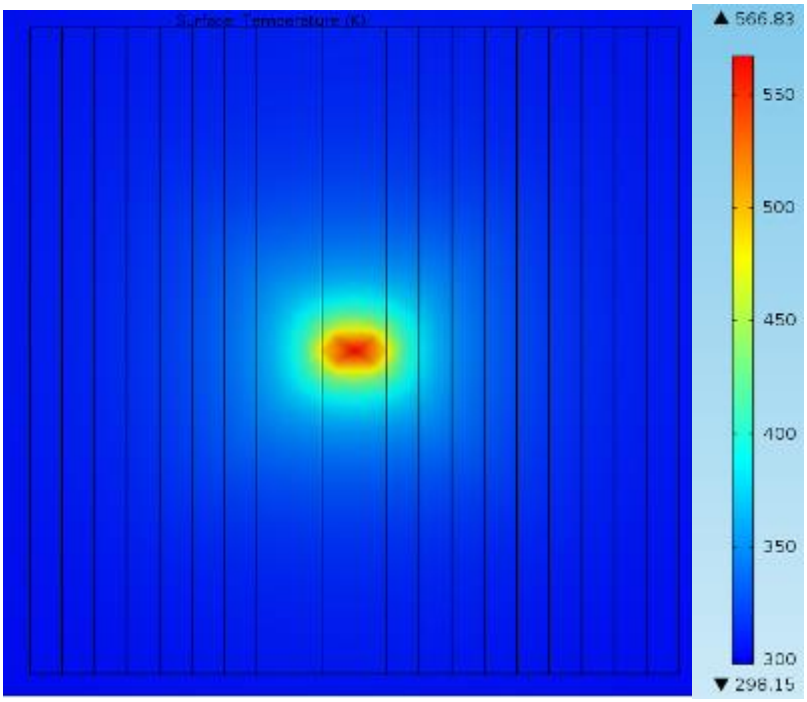

Figure 4: 2D image of temperature distribution on the solar cell

Thermal modelling of AZUR 3C42A (Average & Data 2014: page1) III-V multi-junction PV cell made of GaInP-GaInAs-Ge and area of 1cm^2 to predict its temperature distribution was carried out. Assuming ambient and cooling water temperature of 298.15 K, the cell was placed above a cooling channel with hydraulic diameter of 8.47x10^{-3} m where water flows at a velocity of 0.25m/s. The solar radiation energy received by the PV cell is partially used to generate electricity and the rest is converted to heat. Kerzmann and Schaefer method was used to calculate the amount of input energy that is converted to heat (q_{heat}) as per equation 5 (Kerzmann & Schaefer 2012: page258):

$$q_{heat} = q_{rad} (1 - \eta_{pv}) \quad (5)$$

where q_{rad} is solar radiation incident on the surface of the PV cell, η_{pv} is the cell average electrical efficiency given as a function of thermal coefficient ($\beta_{thermal}$) at each concentration, efficiency at reference temperature (41.4%), and average PV surface temperature (T_{pv}) as shown in equation 6 (Skoplaki & Palyvos 2009: page617):

$$\eta_{pv} = 41.4\% - [\beta_{thermal} (T_{pv} - 298.15)] \quad (6)$$

This converted heat is transferred through the PV cell solid layers by conduction to the water channel where it was dissipated using forced convection. Also, some of this heat is radiated back from the cell to the ambient. Conjugate heat transfer physical model in COMSOL was used to solve the heat conduction and convection simultaneously.

Figure 4 shows the resulted temperature profile using the radiation distribution of the Fresnel lens shown in figure 3; the hot spot on the surface is clear. Although active cooling is applied, the maximum surface temperature reaches to about 567K. Without cooling, the surface temperature of the PV at this level of concentration can reach to 1500K (Min et al. 2009: page03; Theristis et al. 2012: page263). This high temperature is detrimental for any solar cell.

3.1 Effect of increasing the distance between the Fresnel lens and the receiver

Figure 2b shows placing the PV cell further away from the focus point allow the rays to spread over the cell surface. For the receiver located at the focus centre, the predicted Fresnel lens optical efficiency is 78.5% which produces concentration ratio of 491X with received power of 49.07W. Figure 5 shows the variation of received power and the non-uniformity of rays distribution on the surface of the cell with distance from the Fresnel lens. It can be seen that increasing the distance from the lens reduces the non-uniformity but results in significant reduction of the power received.

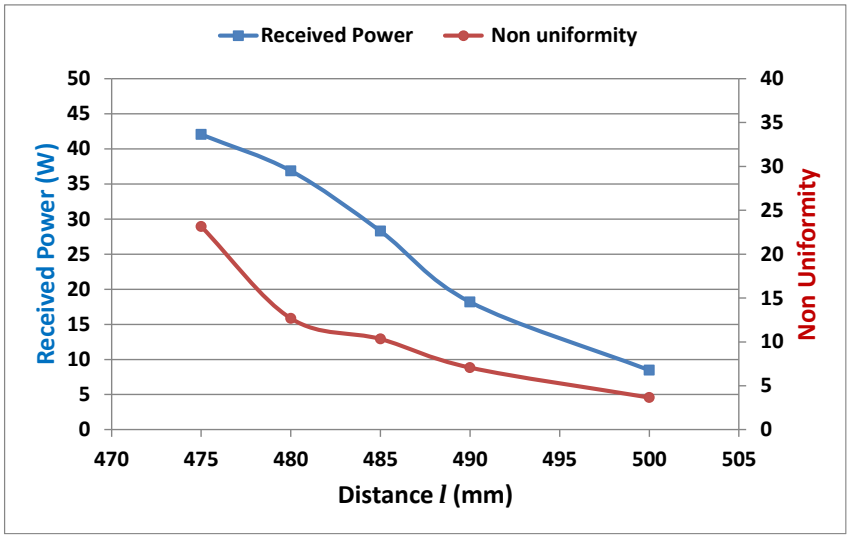

Figure 5: the effect of increasing (l) on received power and uniformity

3.2 Effect of using secondary optical element

A 60mm Squared Miniature Concentrator (SMC) with 95% reflectivity is simulated as a secondary optical element placed above the receiver at *l* =500mm for further improvement (figure 6). Figure 7 shows the rays distribution over the surface of the PV cell placed at l=500mm with the SOE. It can be seen that the energy flux received increased significantly from 8.47W to 48.25W whereas the non-uniformity of rays distribution remained low at 2.79.

Using SOE increased the received power while maintaining the non-uniformity at low value. Table 1 lists the received power, non-uniformity, optical efficiency and concentration ratio obtained with the PV placed at different distances from the Fresnel lens and with the SOE.

Figure 8 shows the resulted temperature profile with the ray distribution of the designed Fresnel lens after increasing *l* to 500mm and adding SOE; the temperature distribution is more uniform. The calculated optical efficiency is 77.2% which produces concentration ratio of 481X. The maximum surface temperature is less than 316K and the average temperature is significantly lower than the case with the PV placed at the focal point.

Figure 9 shows the effect of the secondary optical element height on the uniformity and received power in case of *l*=500mm. It can be seen that increasing the SOE height resulted in decreasing the non-uniformity to reach minimum level at SOE height of 60 mm. Further increase of the SOE height resulted in increasing the non-uniformity. As for the received power, it increased from 40 to 48W with increasing SOE height from 15 to 30mm and remained around 48W until SOE height of 60mm and then decreased with further SOE height increase. 60mm reflector is the ideal height where the surface rays non-uniformity is minimal and received power is maximal.

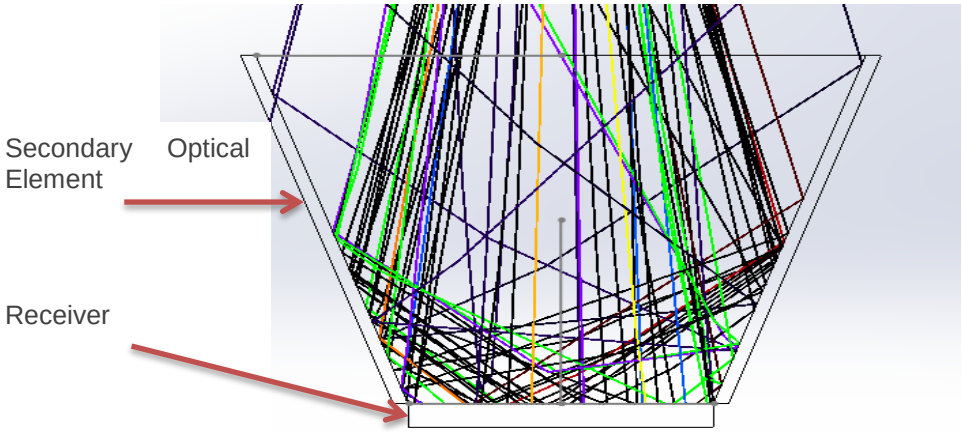

Figure 6: Rays reflected to the receiver by SOE

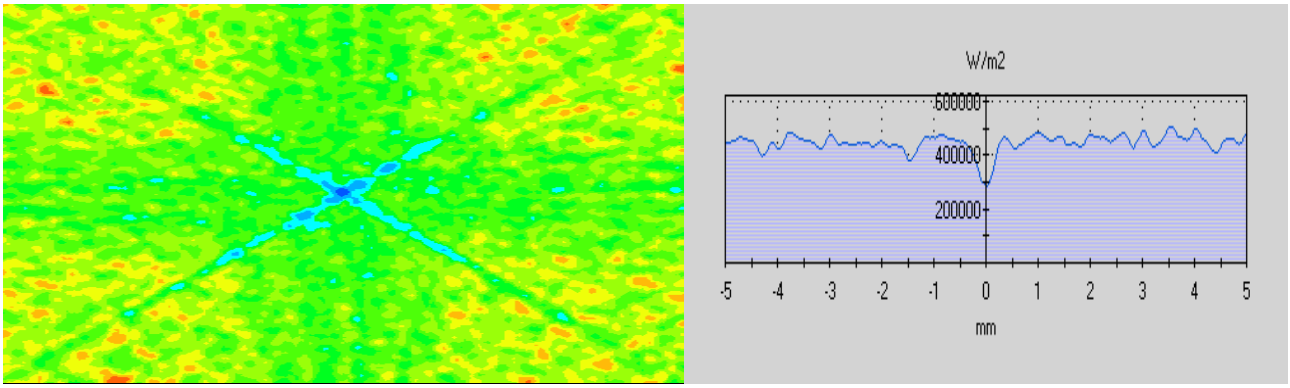

Figure 7: irradiance distribution for l= 500mm including 60 mm height reflector

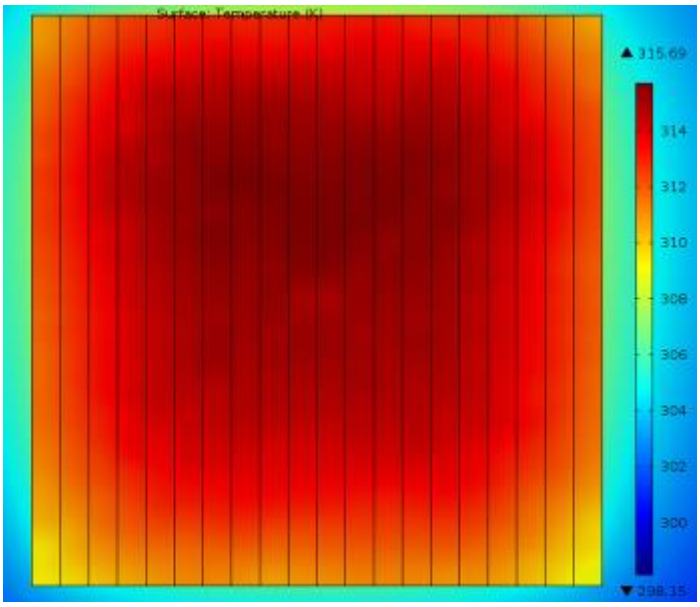

Figure 8: 2D image of temperature distribution on the solar cell

Table1: Simulation results

Case	Received Power (W)	Non-uniformity standard Deviation	Optical efficiency (%)	Resulted CR
original design (*f* = 460mm)	49.07	842.92	78.5%	491X
f =475mm	42.04	23.15	67.0%	420X
f =480mm	36.86	12.68	59.0%	369X
f =485mm	28.27	10.33	45.0%	283X
f =490mm	18.18	7.07	29.0%	182X
f =500mm	8.47	3.66	14.0%	85X
f = 500mm and 60mm height SMC	48.25	2.79	77.2%	481X

3.3 Effect of Secondary Optical Element height

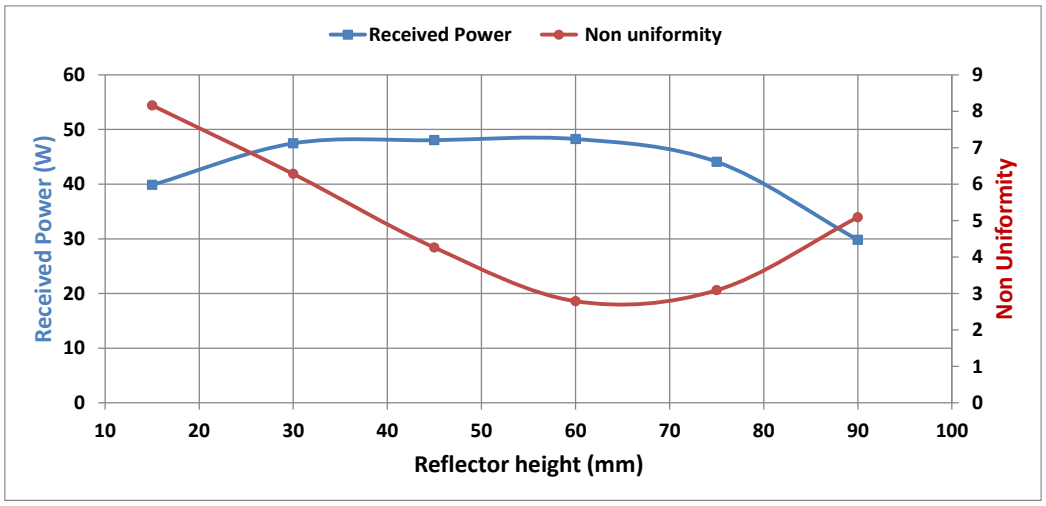

Figure 9: Reflector height vs Received power & non uniformity

3.4 Effect of Secondary Optical Element material reflectivity

Figure 10 shows that increasing the SOE material reflectivity would enhance the received power and as a result the total optical efficiency. The received power increased from about 25 to 50W by increasing the SOE material reflectivity from 50 to 95%. Similarly, the optical efficiency increase from about 40 to 80% by increasing the SOE material reflectivity from 50 to 95%.

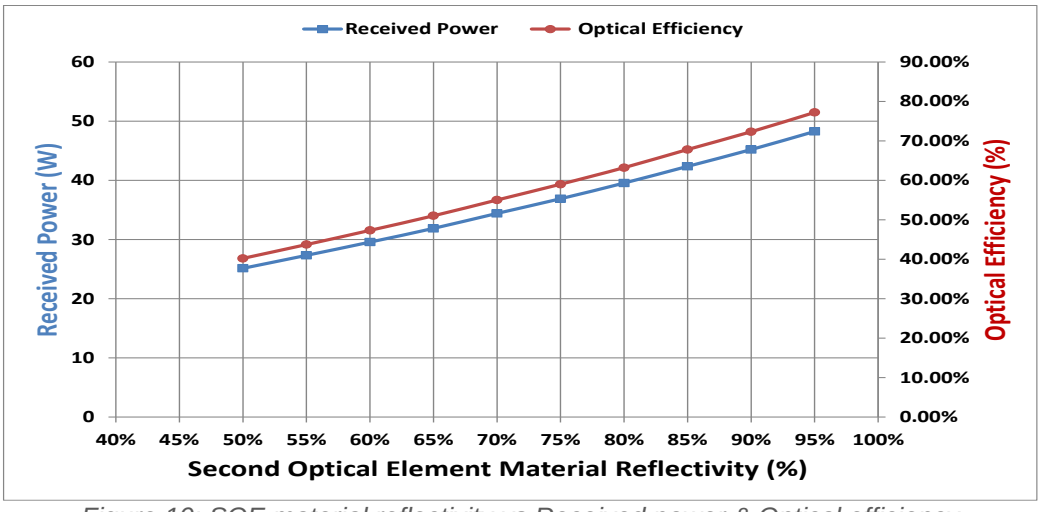

Figure 10: SOE material reflectivity vs Received power & Optical efficiency

4. CONCLUSIONS

Concentrating solar radiation on PV cells has the potential of reducing the number of PV cells used. Received radiation uniformity and hot spot are challenging issues in CPV which needs to be considered when using the Fresnel lens. Ray tracing using advanced engineering software is a powerful tool to analyse the optical performance of solar concentrators and optimise their designs. In this work the effect of varying the distance between the Fresnel lens and the receiver with and without SOE in terms of optical efficiency and illumination uniformity on the solar cell surface was investigated. The optical simulation results showed that increasing the gap between the Fresnel lens and the solar cell from focus position at 460 to 500mm and placing a small square reflector above the PV significantly improve the surface illumination uniformity. Also, simulation results showed that 60mm height SMC made from 95% reflective material is the optimal reflector that can be integrated with the developed Fresnel lens as a secondary optical element. Moreover, higher reflective material for SOE leads to a better optical efficiency and received power by the PV as shown in figure 10. Thermal simulation results demonstrated that PV surface average temperature is much lower after introducing the SOE due to the more uniform energy distribution unlike the case where energy is concentrated in a very small area leading to hot spot.

5. REFERENCES

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