Optical Losses and Durability of Flawed Fresnel Lenses for Concentrated Photovoltaic Application

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**Abstract**

Recycling optical devices and materials for solar concentrator devices is a relatively unstudied area but one which is likely to grow in importance as we progress towards an increasingly sustainable and minimum waste environment. As such, considerations into major optical flaws are required. Here, we have investigated the durability of a cracked Silicon on Glass (SOG) Fresnel lens incorporated as the primary optical component in a concentrated photovoltaic (CPV) application. Optical and electrical characterisations of the flawed glass have been conducted to show the effect on the performance. The optical characterisation has shown a drop of 3.2% in optical efficiency. As well, I-V and power curves of cracked and non-cracked Fresnel lens were compared to shows a drop of 3.2% in short circuit current ($I_{sc}$) and power. The results have confirmed that the power loss is directly related to only the area of the primary optic flawed, which has been calculated through as a percentage of geometrical loss (a form of shadowing) which was estimated to be 2.7% of the concentrator area. From the results, we can confirm that although the performance has slightly declined for the significantly flawed Fresnel lens, there are no other detrimental optical effects. The durability of such optics still needs to be tested, but from these results, we recommend that similarly critically flawed optics can be utilised, likely in non-demanding singular CPV units where < 5% loss is acceptable.

**Keywords:** Fresnel lens, optical efficiency, concentration ratio, Concentrator photovoltaics, optical and electrical characterisation

## 1. Introduction

Refractive concentrator photovoltaic (CPV) systems typically utilise Fresnel Lenses to collimate and focus solar illuminations onto a smaller solar cell which is economically advantageous by minimising the required photovoltaic (PV) cell area [1]. The Fresnel lens is commonly exploited as a primary optical interface in focal point CPV systems due to its high optical efficiency and acceptance angle in comparison to reflective paraboloid–hyperboloid optical shapes. However, mechanical fragility of glass rises its vulnerability for cracking due to external physical impact and such optics are typically abandoned/wasted. The waste expenses in the United Kingdom (UK) glass manufacturing is a minimum of £15 billion/a year which is about 4.5% of the total revenue [2]. Glass recycling practice aids both UK glass industry by applying the waste minimisation program (reduce cost by 1%) and ensure the UK countries to meet European (EU) Directive target of at least 60 % of glass recovery/recycling rate [3]. Most of the studies are investigating the glass cracks and their characteristics (length, depth, and angle) for the laser damage performance but none of which has studied glass cracks for CPV applications [4–7]. In these other studies, artificial scratches were made on Fused Silica glass to study the effect of the laser transmittance and show that the ductile scratches have less influence on the transmittance of light in comparison with brittle scratches[8]. Further, the effect of brittle scratches on transmission was carried out for a set of K9 glasses. The results indicated that the brittle scratches reduce the transmittance of light; but increasing the chemical etching time for the K9 glass improves the transmittance of light especially for high density cracked samples [9]. Even a small optical flaw or crack made leads to sever hot focal spot effects that either degrade the lifetime of the solar cell or damage it, and also this small optical flaw causes a significant loss to an arrayed CPV system as all series optics would be limited by the performance of the flawed optics. However, these mechanical concerns contain loss of physical strength of Silicon on Glass (SOG) Fresnel lens and its influence on the optical and electrical performance for CPV application are notably absent from the literature [10,11]. Thus, this article aims to investigate the power output, optical efficiency (loss of transmittance) and durability of a cracked Fresnel lens (SOG) in comparison with a non-cracked one to confirm if such broken optics are more or less still fully functional or worthy of recycling, perhaps for less demanding systems (local/educational projects) with singular unit systems rather than full scale power plants.

## 2. Experimental Approach

Optical and electrical characterisation approaches were conducted for the unflawed and flawed lenses (23 × 23 $cm^2$) (Figure.1 a) utilising both a PerkinElmer spectrophotometer and solar simulator (WACOM). Firstly, the unflawed and flawed lenses were optically characterised by measuring their total transmittance for every wavelength in the range of 400 – 2000 nm. Secondly, at 1000 $W/m^2$ solar irradiance, the lenses were adjusted in height to assure the optimum focal spot and length, as in Figure.1 b. Afterwards, a multijunction solar cell Azur space (10 × 10 $mm^2$) (Figure.1 c) [12], was positioned in the centre of the focal spot for I-V curve measurements for each lens.

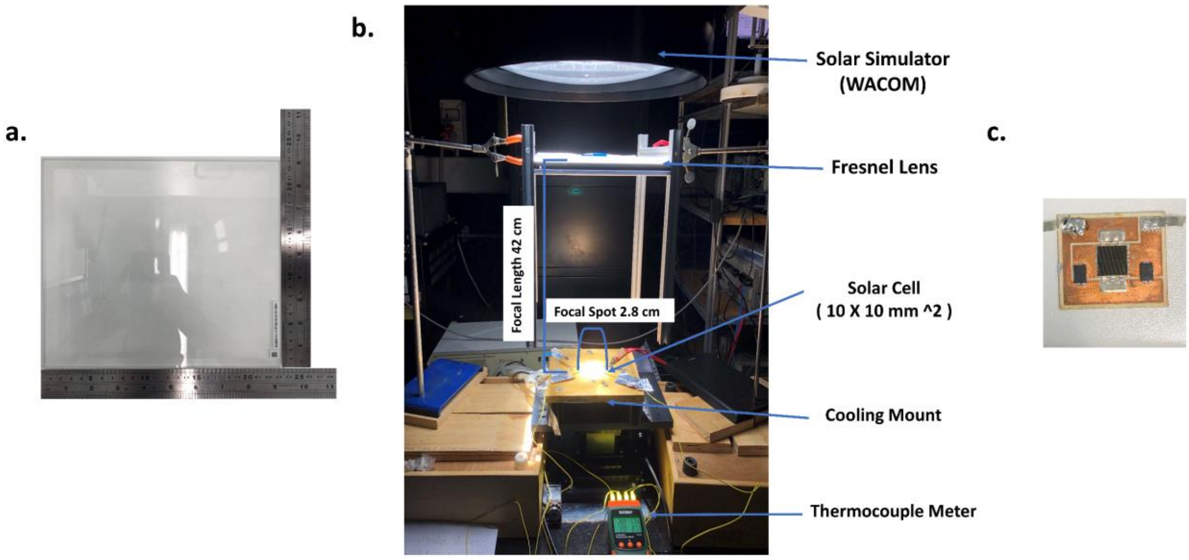


**Figure 1 a) Fresnel lens (SOG) (23 × 23 cm$^2$). b) experiment setup under WACOM Solar Simulator. c) IIV Azur space 10 × 10 mm$^2$ solar cell.**

The temperature range of the solar cell is a further consideration; the solar cells requiring below 80 °C to perform electrically well [13]. A cooling mount base was hence utilised to maintain the cell at 25 °C whilst under the concentrated light. Also, a thermometer was attached to the solar cell surface and the cooling mount base to observe temperature simultaneously and to avoid any damage of the cell and assure proper electrical performance.

## 3. Results and Discussion

The adjustment of the Fresnel lens under the solar simulator results in a focal length of 42 cm and a focal spot of 2.8 cm, as in Figure 1.b. Since the solar cell area is 1 cm$^2$, the utilisation of the focal spot is merely 16% which can be considered as a focal spot loss that although will compromise both the optical and electrical performance, should affect both lenses equally. As in Figure 2, the percentage of the crack size to the full Fresnel lens area is estimated to be 2.7%.

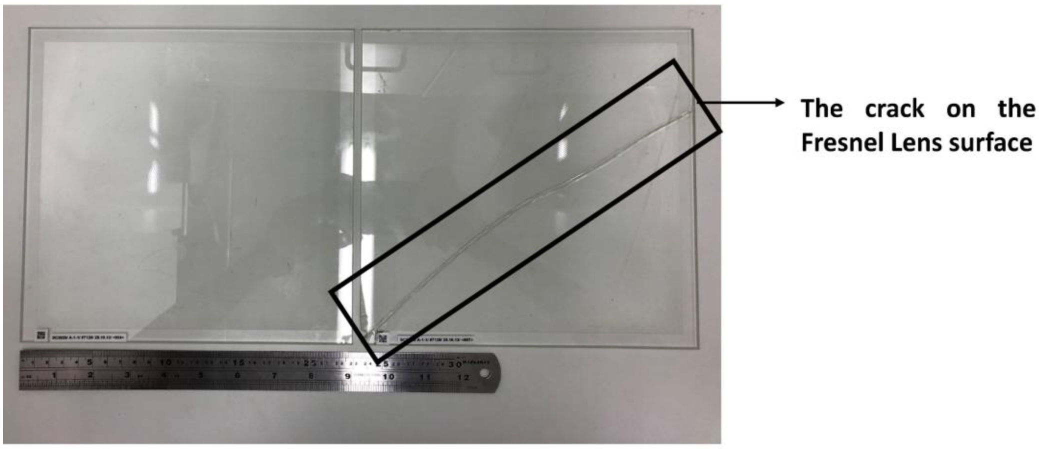


**Figure 2 the flawed/ unflawed Fresnel lens.**

## 3.1 Optical characterisation

The optical efficiency was calculated with respect to the total transmittance at every wavelength unit as in equation (1).

$$\boldsymbol{Oppeff} = \%\boldsymbol{T} \times \%\boldsymbol{C} \qquad (1)$$

Where Oppeff is the optical efficiency, %T is the measured total transmittance of the Fresnel lens, and %C is the fractional concentration loss (fraction of the cell area to the focal spot area). The fractional concentration loss is due to the limit of which the Fresnel lens geometric design cannot concentrate solar rays to a focal spot as the solar cell size.

The optical concentration ratio $C_o$ is calculated with respect to the optical efficiency and geometrical concentration ratio $C_g$ and can be done similarly at every wavelength unit as in equation (2).

$$\boldsymbol{C_o} = \boldsymbol{Oppeff} \times \boldsymbol{C_g} \qquad (2)$$

These calculations result in Figure 3.a, where the lens optical efficiency was found to be an average of 91% and 88% and hence the concentration ratio (primary optic area/cell area) after the Fresnel lens would be 480 suns and 463 suns for the non-cracked and cracked Fresnel lenses, respectively. The consideration of the fractional concentration loss as described previously,(due to focal spot area being larger than cell area) into the previous equations results in system optical efficiencies of 15% and 14% and optical concentration ratios of 78 suns and 75 suns for the non-cracked and cracked Fresnel lenses, respectively. All displayed in Figure 3.a. All successive optics performance in the singular CPV unit will be dependent on the performance of primary flawed/unflawed Fresnel lens.

a.

b.

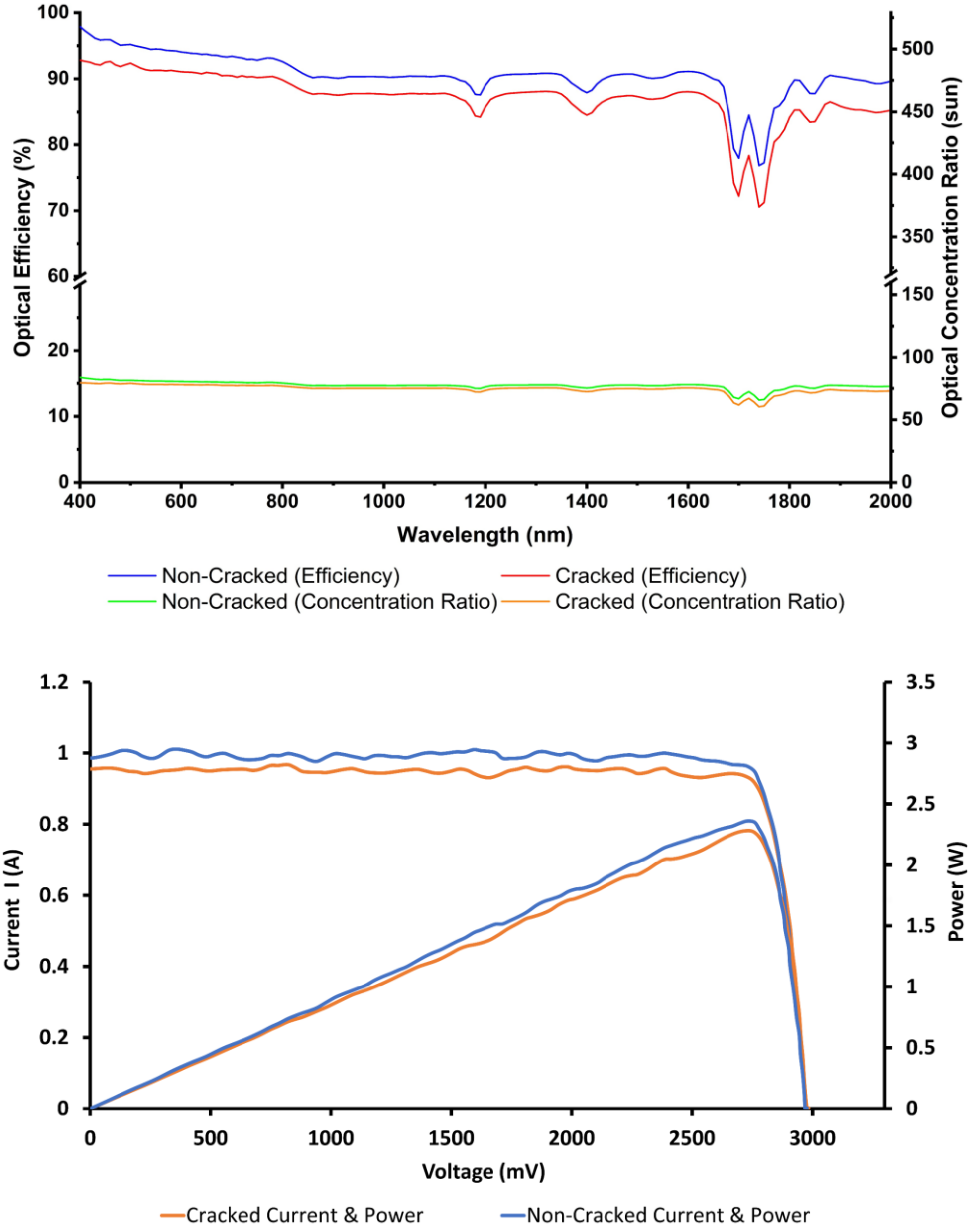

**Figure 3 a) optical efficiency and optical concentration ratio (calculated using the solar cell area as a final optical stage) lines for the flawed/unflawed Fresnel lens. b) I-V & power curves for the flawed/unflawed Fresnel lens.**

### 3.2 Electrical characterisation

The solar simulator helicon lamp was adjusted to illuminate solar irradiance of 1000 $W/m^2$ for electrical characterisation. Thus, as in Figure 3.b, I-V curves show a short circuit current ($I_{sc}$) of 0.985 and 0.954, and the power curve shows a maximum power of 2.35 W and 2.275 W for non-cracked and cracked Fresnel lens, respectively. The optical and electrical characterisation has shown an agreement in the performance drop of non-cracked to cracked Fresnel lens by about 3.2%. This drop of performance is slightly higher than the percentage of the crack size, which we consider as a geometrical loss % (shadow) in the focal spot. The difference is due to the limits with which the crack size can be estimated. The altered irradiance distribution upon the cell (due to the crack) would not add to efficiency loss since temperature profiles upon cells are rarely as discreet as the incident light profile. As in Figure 3.b, open-circuit voltage ($V_{oc}$) and fill factor (F.F.) were observed to be quite similar for both non-cracked and cracked Fresnel lens indicating no temperature impact because open-circuit voltage ($V_{oc}$) is temperature-dependent. As well, in these measurements the thermocouples attached to the cell back and top remained at 25 °C. On the other hand, the reduction in the $I_{SC}$, which is dominated by the solar irradiance intensity, from the non-cracked and cracked Fresnel lens is the only indicator for the drop in the power curve. Thus, all these justifications are affirmed that the drop-in performance is due to only the hinder of solar irradiance by the percentage of the geometric loss not to any other optical, thermal, and electrical factors. Although the Fresnel lens is significantly flawed, still the amount of optical losses compromised on the electrical performance is within a reasonable level of less than 5 % allowing the utilisation of such an optic as a primary optical stage in non-demanding CPV unit.

## 4. Conclusion

The optical and electrical characterisations of flawed SOG Fresnel lens is adopted to see its durability in CPV systems. This approach allows to estimate the percentage of the crack size to the overall Fresnel lens area, and then estimate the optical performance (optical efficiency and optical concentration ratio) and investigate its influence on the electrical performance. The optical and electrical performance has shown a similarity in the percentage decay but when sizing the shadow of optical flaws, overestimation may be the safer procedure as difficult to estimate size visually. A loss of 3.2% optically and electrically should be low enough for similarly flawed and damaged optics to still be used or recycled for low demand projects and installations. The durability of such systems however requires further study.

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