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Reliability Investigation for a Built Ultrahigh Concentrator Prototype

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Abstract. Ultrahigh concentrator photovoltaics hold a great potential in both reducing the cost of photovoltaic energy and to higher conversion efficiencies. The challenges in their design and manufacturing however have not yet permitted a reliable ultrahigh (>2000X) system. Here we propose an ultrahigh concentrator photovoltaic design of 5800X geometrical concentration ratio based on multiple primary Fresnel lenses focusing to one central solar cell. The final stage optic is of a novel design to accept light from four different directions and focus the light towards the solar cell. The extremely high geometrical concentration of 5800X was chosen in anticipation of the losses accompanied with ultrahigh concentration due to alignment difficulties. The system was designed with manufacturability as one of the priorities and resulted in easily achieving >2000X concentration for a first prototype with non-achromatic Fresnel lenses and in house secondarys. Higher concentrations are anticipated for future prototypes but investigation into the cell performance is required. An acceptance angle of 0.4° was achieved for this design which is considered good for such an ultrahigh concentration level and what's more, even at higher misalignment angles (such as 0.8 or 1 degree) ultrahigh concentration ratios are still achieved in simulations. Such a design could be the breakthrough in concentrator photovoltaic research for reaching higher concentration ratios. The use of flat optics to ease manufacturing and alignment is a simple but effective method to achieve a reliable system that will achieve ultrahigh concentration even at 36% optical efficiency. Such a design will be of use in investigations of concentration, concentrator solar cell development, temperature effects and more; achieving ultrahigh concentration levels not yet tested.

INTRODUCTION

One trend in concentrator photovoltaic (CPV) technology is towards systems of higher concentration levels[1–3]. This is due to their ability to increase cell conversion efficiencies and reduce cell size, also reducing the photovoltaic cost contribution to the full system[4,5]. Multi-junction solar cells are pushing higher and higher efficiency records within relatively short time spans and need equally progressive concentrator optical designs to match. The main design constraint for the optics of high (100-2000suns) and ultra-high (>2000 suns) CPV systems is the difficulty to achieve a high tolerance design which is simultaneously of a high optical efficiency. This is ultimately due to the limits of etendue but is also affected by material availability and manufacturing accuracy [5–8]. Temperature is another key issue in ultrahigh concentration designs but as long as the light distribution upon the cell is relatively uniform and there is sufficient cooling (passive or active), then it is manageable. There has already been research into the effect of high temperatures on Fresnel lenses[9–11] and the ability of passive cooling plates to accommodate ultrahigh concentration ratios[12,13].

Fresnel lenses as a primary concentrating optic have a relatively good acceptance angle and optical efficiency in comparison to the cassegrain design utilising conic primary reflectors[1]. If used alone, a single medium Fresnel lens is limited in concentration ratio by chromatic aberration to ~1000 suns[14]. Achromatic Fresnel lenses made of 2 mediums as described by Languy et al.[14] and Vallerotto et al.[5] can achieve higher concentration ratios but still need to reach full scale manufacturing. The other option for ultrahigh concentration is to incorporate multiple concentrating optics in a singular system but too many can significantly reduce the optical efficiency and tolerance. In this paper we present an ultrahigh design of geometric concentration ratio >5800x in anticipation of high optical losses and assume relatively standard optics even though a higher optical efficiency can be obtained with state of the

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art materials and lenses. In this way this study will not only present a new type of ultrahigh concentrator that can be built with current standard optics but which will only improve as the prototype, optical research and manufacturing develops.

Another constraint in achieving ultrahigh concentration ratios is fabrication limits, the size of Fresnel lens or conic mirror required would be costly and difficult to manage. To overcome this we propose the use of 4 Fresnel lens's focusing to 1 central PV cell with the aid of other redirecting and concentrating optics. A similar method has been adopted by Ferrer-Rodriguez et al. who recently proposed a design consisting of 4 cassegrain style reflectors which were angled to focus onto a central receiver optic and PV cell[15] . We compare our concentrator design to this as well as others to show its advantages despite the likely lower optical efficiency.

If reliable easy to manufacture ultrahigh concentrator photovoltaics were demonstrated then the cost effectiveness and further development of CPV technologies would expand greatly. The initial costs of CPV technology are still too high and the benefit of higher concentration systems has been clouded by high prototyping costs and in field challenges.

DESIGN

For this design we chose 4 square Fresnel lenses (silicone on glass) with focal lengths of ~46cm and aperture dimensions of 21cm by 21cm each. For the receiver we use a 5.5mm x 5.5mm multi-junction solar cell. This gives us a geometric concentration ratio of 5831X. In order to gather the light towards the centre we propose the use of flat mirrors and a central refractive optic made up of 4 dome lenses as shown in figure 1.

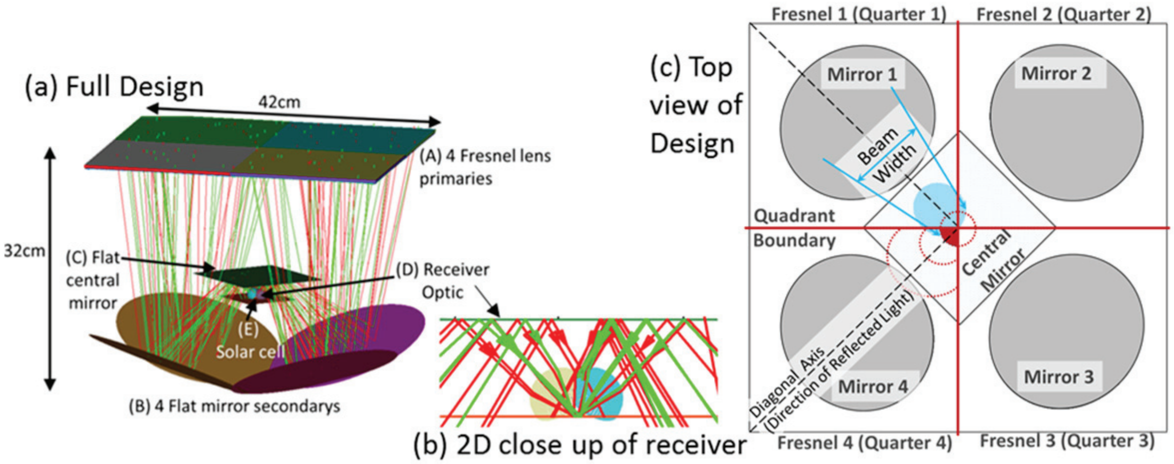

FIGURE 1. (a) Ray trace diagram of ultrahigh concentrator showing 4 square Fresnel lenses focusing towards 4 angled flat reflectors. The light it reflected again by a central flat mirror onto a central refractive optic coupled to the solar cell. (b) A 2D close up of the receiver optic. The green and red rays represent 400nm and 1600nm light respectively. (c) Top view of the design showing the 4 quadrants of the system dictated by the 4 primary lenses each with their own flat mirror aligned underneath.

In order to keep the design as simple as possible and minimise losses due to manufacturing inaccuracies flat mirrors were used instead of conically shaped ones. By using flat mirrors the reflectance can be very high (e.g.~97% above 450nm with protected silver [16,17]) even in the prototyping stage since no complicated shapes are involved which would either be expensive to manufacture or very difficult to attach reflective film to. Accurately manufacturing large smooth shapes of metal is also very challenging if intending on using vacuum metalizing methods to coat the metal into a mirror[18] . Aligning the mirrors with their specific angle of inclination will also be easier if they are flat. A central flat mirror as the third optical stage was also chosen to allow for an upward facing solar cell and cooling mount.

OPTICAL QUALITY

Due to the accuracy required for ultrahigh concentrator optics, thorough simulations as well as some measured optical properties (figure 2) were carried out to ensure the design was modelled accurately. The quality of the optics plays a significant role in the achieved optical efficiency[18–21] which is why 'optimistic' simulations were avoided. The optics utilised in the first built prototype included a standard silicone on glass Fresnel lens as measured in figure 2A, >95% reflective mirror film as measured in figure 2B and a refractive centre optic made of Sylgard with transmittance spectra measured and shown in figure 2D. The performance of the system would benefit greatly however with a higher refractive index centre optic such as sapphire as shown in figure 2C[22] but for an initial proof of concept prototype a lower refractive material was used.

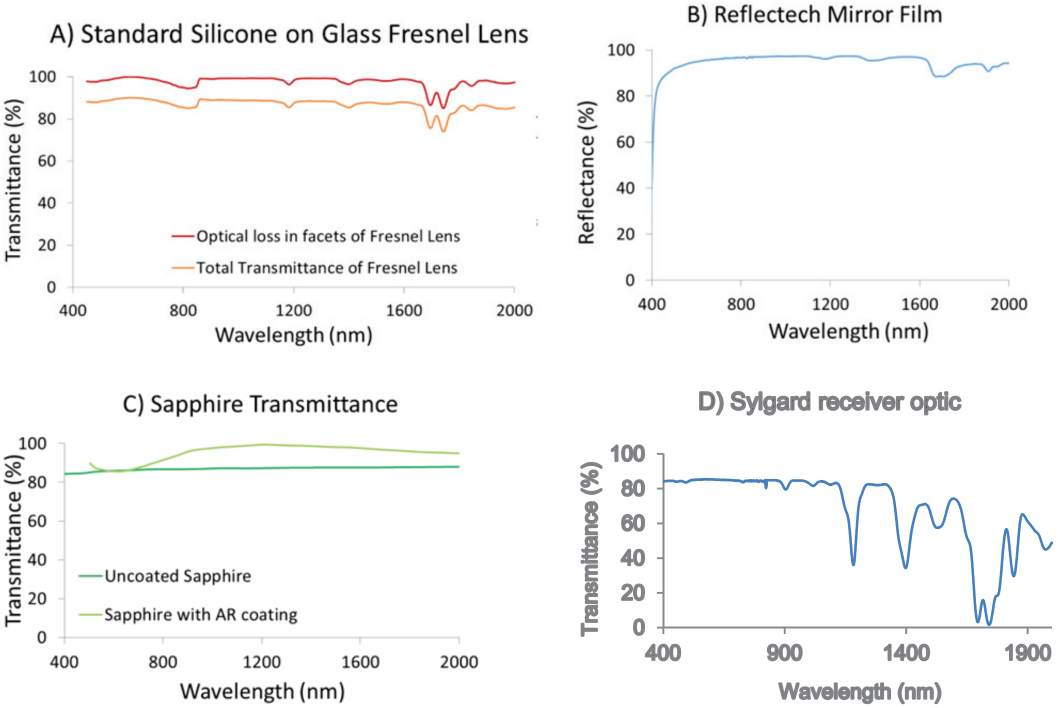

FIGURE 2. (A) Measured transmittance of Fresnel lens using pane of glass as a reference to measure scattering within facets. (B) Measured reflectance of Reflectech mirror film. (C) Transmittance of common Sapphire and Sapphire with antireflection coating[23] (D) Transmittance of dome receiver optic made of Sylgard.

A reflectance of >95% should be easily achievable with flat mirrors in place. The reflectance of one of Reflectech's mirror films (figure 2B) is shown to have slightly above this for most of the wavelength range absorbed by the intended solar cell (400-1600 nm).

One key unknown attribute is the surface quality of the centre optic which could reduce the optical efficiency in figure 3A below by another 4-7%[22,24] depending on the material and surface finish. Anti-reflection coatings are also a possibility to improve performance, especially if a high refractive index material is used in future prototypes. The acceptance angle can also be effected by the manufacturing accuracy of these optics. The acceptance angle for the proposed design was found to be 0.4° according to the simulation results given in figure 3.

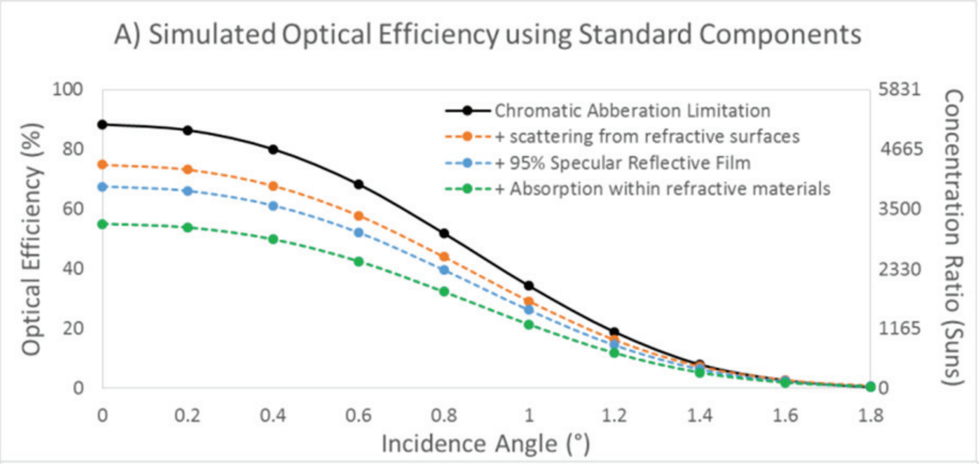

FIGURE 3. (A) Simulated optical efficiency of the concentrator using standard components including a silicon on glass Fresnel lens, flat 95% reflective mirrors and an uncoated refractive index (~1.5) centre optic.

The final predicted optical efficiency is of ~55.12% for the intended prototype, this corresponds to >3000 suns (3000x concentration) as shown in figure 3. The optical efficiency of 3A can be improved by the use of achromatic Fresnel lenses, 98% reflective silver mirrors and a high quality Sapphire (or similar high refractive index material) centre optic with AR coatings. Such improvements would reach an optical efficiency of 75.03% but will require further research especially for the cell performance under such a high resulting concentration ratio. The best material for the centre optic is in particular need for further research in terms of performance and cost. Sapphire has the right properties but may initially be costly for the unique shape tooling. At present cheap sapphire half ball lenses can be purchased (<$40 [25]) and could be moulded together with another material to make the centre optic however their performance is untested for these applications. There are other options of plastics, glasses and coatings which would also achieve the desired optical properties similar to sapphire desired here but require further investigation. The shape itself is not costly to manufacture a mould of as it requires standard circular shaped drills of the appropriate size.

BUILT PROTOTYPE

The first prototype was built using non-achromatic Orafol Fresnel lenses, Reflectech mirror film on metal for the flat mirrors and a moulded Sylgard receiver optic. The mould for the receiver optic was manufactured in house and mechanically polished. Due to the simple dome curves used in the receiver optic, manufacturing was relatively easy as was the polishing although the hand held polishing machine could still have altered the shape slightly.

For this experiment the solar cell used was designed for 500X concentration and as expected the efficiency decreases as concentration ratio and temperature increases[2]. With increased concentration ratio there is increased current density which leads to higher resistive losses and heating within the cell. In particular the tunnel junctions within the cell can break down due to this increased thermal load[26,27]. The current density can be reduced by increasing the number of front electrode grids but these also take up space and reduce the active area of the cell. The temperature of the solar cell under increased solar concentration ratios is still to be investigated and compensated for which has not yet been covered by this study. Initial testings however did show in one instance a solar cell assembly coming apart due to the high temperatures, both the cell and the electrode connectors lost connection and reconnected in a different orientation. Although some indication of the concentration-efficiency and temperature-efficiency relationships is given by the company Azurespace [28] and other studies2, there is still a lack of research to give accurate analysis of the cells working efficiency. An indication of the optical efficiency and concentration ratio achieved would hence be very difficult to back calculate from the results of a fully illuminated prototype (>2000X). For this reason ¼ of the ultrahigh system (1 of the square Fresnel lenses in figure 1)) was illuminated and the I-V measured as shown in figure 4. This results in a geometrical concentration of 1764X and according to the simulated optical efficiencies in figure 3 would give an effective concentration ratio of ~972X at normal incidence. Due to the symmetry of the system as can be seen in figure 1c each quarter is identical and so if the optics work in one quarter, they should work in all 4 assuming central alignment. If all 4 Fresnel lenses were illuminated the predicted effective concentration would be ~3888X.

The ¼ illuminated prototype produced a maximum of 2.44A (figure 4) which corresponds to an estimated 525X following its reported performance by Azurespace28. In this way it can be extrapolated that full illumination of the prototype (all 4 lenses) would achieve ~2100X effective concentration ratio proving the UHCPV optical design. The solar cell was thermally attached to a large metal heat sink and illuminated only briefly to avoid reaching high temperatures or risk damage due to the possibility of ultrahigh concentration spots and resistive losses as discussed previously. This concentration ratio relates to an optical efficiency of ~36% but still achieves the criteria of ultrahigh concentration as desired. The acceptance angle of the system has not yet been accurately measured but the prototype itself is estimated to have ~0.8° worth of misalignments which would explain the lower optical efficiency when looking at the simulated results in figure 3A. These results are very promising for an initial prototype as the alignment during assembly has still to be improved and made exact for optimum performance but nevertheless ultrahigh concentration is already being achieved. The fact that such a result was obtained even for a very basic initial prototype supports the reliability of this relatively simple but effective design incorporating flat optics. The use of a higher refractive index receiver optic will also increase the concentration ratio and optical efficiency further as well as the use of appropriate antireflection coatings. In this way an ultrahigh concentration of ~3000X can be achieved with systems of overall accuracy (tracker, mounting, manufacturing…) ±0.5° alignment and ~2000X with systems of overall accuracy ±0.8° as suggested by figure 3A. However consideration of the cells performance and which cell type would perform best over prolonged use in such a system has next to be carried out along with temperature measurements.

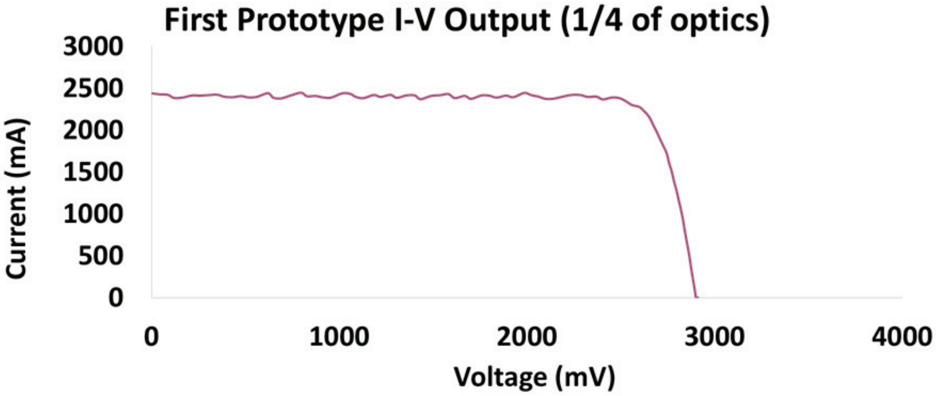

FIGURE 4. I-V trace of the first ultrahigh prototype under 1000W/m^2.

DESIGN COMPARISON AND DISCUSSION

A comparison table is given below (Table 1) which compares the presented design to others in the literature. As can be seen higher concentration ratios can achieve higher concentration acceptance products (CAPs) but tend to have lower optical efficiencies. This may be due to the higher number of optical stages or due to the higher priority given to maintaining an adequate acceptance angle. The number of stages shown in table 1 includes the entrance and exit of light through optics, also including the cover glass as these interfaces will contribute to scattering and light ray deviation which in turn contributes to the acceptance angle of the system as well as the optical efficiency. In this way, although the ultrahigh concentrator contains 2 flat mirrors which might seem unnecessary, the number of optical stages is similar to the Cassegrain ultrahigh concentrator but with the advantage that the flat optics will be far easier to manufacture and position with high accuracy in comparison to the curved mirrors of the ultrahigh cassegrain design. The manufacturing difficulty is a qualitative measurement based on the need for large smooth curved optics. The cost is assumed to be similar but really depends on scalability. At the prototyping stage flat, small or off the shelf shapes will always be cheaper. The proposed design takes advantage of this.

The 'power output per area of PV' in Table 1 assumes 1000W input to each system (scaling all systems to 1m^2) and does not include the efficiency of the solar cell. These results show which designs would be best depending on the priority and highest component costs. For example, if minimising the amount of PV material was the highest priority, which it typically is, not only due to costs but due to the toxicity of some cell materials, then the higher the concentration the better. If space was the most valuable commodity then the highest optical efficiency designs are of course the most desirable. Depending on the cost of the cells and the cost of the optics a compromise between the concentration ratio, optical efficiency and acceptance angle will result in the most cost effective design but will strongly depend on the scalability of manufacturing such systems. These considerations are very important when we think of the motivation for CPV, is it efficiency, cost or space restrictions? Typically large plants and projects are not limited by land use and hence in theory are driven more by reliability, manufacturability and cost effectiveness instead of directly the optical efficiency. This design prioritises manufacturability but maintains a high potential for high optical efficiencies and acceptance angles as well as high conversion efficiencies for solar cells due to the ultrahigh concentration ratio. The ultrahigh concentration ratio also allows for minimisation of the solar cell costs and hence in theory should be more environmentally friendly.

TABLE 1. Comparison table including concentration-acceptance angle product (CAP) analysis.

Concentrator Design Type	Ultrahigh Concentrator under study (Sim.)	4-off-axis Cassegrain[15] (Sim.)	Mini-Cassegrain Concentrator[29] (Exp.)	Dome shaped Fresnel Lens[30] (Sim.)
Geometric Concentration Ratio	5831X	2304X	1037X	506X
Acceptance Angle (°)	0.4	0.61	0.75	0.5
Geometric CAP	0.533	0.51	0.42	0.20
Optical Efficiency	State of the art optics: 75% Standard optics: 55%	73%	80%	90%
Effective Concentration Ratio	State of the art optics: 4373X Standard optics: 3214X	1682X	800X	455.4X
Effective CAP $\left(\sqrt{C_{\text{Eff}}}\ \sin\alpha\right)$	State of the art optics: 0.46 Standard optics: 0.39	0.44	0.37	0.19
Solar Cell Size (mm^2)	5.5x5.5	5x5	1x1	1.4x1.4
Power output per area of PV utilised.	Simulated 75%: 4.35W/mm^2 Prototyped 36%: 2.09W/mm^2	1.68W/mm^2	0.83W/mm^2	0.
No. of Optical Stages (including entry/exit of cover glass)	5	5	4	3
Manufacturing Difficulty	Medium	High	Medium	Medium-High
Cost Estimate	Average	Expensive	Average	Average-Expensive

CONCLUSION

An ultrahigh concentrator photovoltaic system is presented and the different cases for non-ideal optics have been analyzed. The design takes advantage of flat mirrors and easy manufacturing methods in line with current and state of the art optical capabilities. The system can theoretically achieve an optical efficiency of 75% which is >4300x but with standard quality optics still achieves >3000X with an optical efficiency of 55%. The system has a theoretical acceptance angle of 0.4° which is very good for such levels of ultrahigh concentration and of a relatively simple design. The design is easy to manufacture 1/4 of the built prototype reliably achieved 525X which due to the symmetry of the design results in an ultrahigh concentration of >2100X when the prototype is fully illuminated. Unfortunately a suitable solar cell was not available at the time of testing to fully illuminate the prototype inpute area (4 Fresnel lenses) and the optical efficiency (~36%) can be improved with a higher refractive index material for the central optic. In order to achieve higher efficiency solar cells the concentration should also be increased and this system reliably does this even with relatively cheap optics and simple alignment methods. Research will continue on this design to improve the optical efficiency but this is a good starting point for this design and may pose of great use to other lines of research requiring ultrahigh concentration ratios and temperatures. The ease with which the 2000X mark was reached for this prototype as well as the CAP value and potential benefits detailed in Table 1 also substantiate the advantages of designing with manufacturability as one of the priorities.

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