LUMINESCENT SOLAR CONCENTRATORS: CYLINDRICAL DESIGN

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Luminescent solar concentrators (LSCs) are typically planar low-concentration systems that absorb sunlight over a large area and emit a red-shifted spectrum out of smaller surfaces, where solar cells can be attached. We present the study of a composite system, in which a linear geometrical concentrator is used as primary device to focus sunlight onto a cylindrical LSC encased in a transparent matrix. The idea behind this design is to reduce re-absorption losses, which generally limit the performance of LSCs. Experimental measurements on a cylindrical LSC were compared with a raytrace model, showing a good agreement. Further predictions were made based on the model. It was shown how the reduction of re-absorption losses is achieved by allowing the luminescence from the cylindrical core to travel in the transparent matrix. The proposed design can achieve high optical concentrations with the need for only one-dimensional tracking.

Keywords: light trapping, concentrator, ray tracing

1 INTRODUCTION

The luminescent solar concentrator (LSC) was proposed in the 1970s [1, 2] as a way of spectrally modifying and simultaneously concentrating light for conversion by photovoltaic (PV) cells. In its conventional use, the LSC has a planar architecture and collects sunlight over its entire front surface. Luminescent materials absorb the incident light and re-emit it at longer wavelengths. Through total internal reflection a large fraction of the luminescence is trapped within the plate and guided to the edges, where it can be coupled into PV cells. The geometric ratio between the collection area and the emission area leads to a concentration of the light. Additionally, LSCs can increase the conversion efficiency of the attached PV cells through spectral modification of the light. By replacing the majority of photovoltaic cells by relatively cheap materials, the costs of the PV system can be reduced. LSCs can efficiently collect diffuse irradiation and direct irradiation incident at oblique angles, eliminating the need for solar tracking.

Not much research has been published on cylindrical LSCs. Batchelder [3] used this geometry for the study of self-absorption. More recently, a theoretical comparison of cylindrical and square-planar LSCs was carried out by McIntosh et al [4], showing that the optical concentration of the cylindrical LSC can be up to 1.9 times higher than that of the planar. They also proposed a multi-cylindrical structure made up of many cylinders aligned side by side to yield further enhancements.

The design we present in this paper differs from those aforementioned as it comprises a composite LSC structure for use as a secondary device in a high concentration system.

2 CONCEPT

In this composite design, a relatively thin cylindrical rod containing luminescent material is encased in a transparent bar, as shown in Figure 1. The refractive indices of these two components are matched so that light is not bound by the interface between them and can travel in the entire composite. Sunlight is focused in one dimension onto the length of the cylindrical core using a geometrical concentrator, such as a linear Fresnel lens or an array of lenses. The PV cells are attached at the two end surfaces of the bar.

A major loss mechanism in LSCs is the re-absorption of luminescence, which can result in escape cone and non-radiative losses. The motivation behind the composite design is to achieve a reduced probability of re-absorption. This is possible because the cross-section of the core is small compared to cross-section of the transparent bar. Therefore, luminescence travelling in the composite has a smaller chance of being in the core where it could be absorbed.

Compared to a conventional planar LSC that would cover the entire area of light collection, i.e. the area of the Fresnel lens, the composite design requires a smaller area to be covered with PV cells. This cost reduction, however needs to be weighed up against the additional cost of the primary concentrator, which would also require one-dimensional solar tracking. A significantly larger optical efficiency could make this design viable for application.

Figure 1: Schematic of the composite cylindrical LSC comprising a cylindrical core with the active material encased in a transparent cuboidal matrix, designed for use with a primary geometrical concentrator focussing light in one dimension onto the core.
3 EXPERIMENTAL CHARACTERISATION

The cylinder shown in Figure 2, made of a polymer doped with the dye Fluor Yellow, with a length of about 40cm and a radius of 2mm was used for the experimental measurement. The dye emits in the green with a luminescence quantum efficiency (LQE) of 95%. It has a relatively small Stokes shift and a narrow absorption band, which means that this concentrator is not optimised for a high yield under a broad spectrum.

Figure 2: Cylindrical core containing the luminescent material (Fluor Yellow dye).

In order to investigate how well this cylinder guided incident light to the end surfaces, a distance dependent optical response measurement was carried out. Figure 3 shows the setup, in which a laser was used to illuminate spots along the length of the cylinder while the photocurrent out of one end was measured with a photodetector.

Figure 3: Experimental setup using a red (404nm) laser and a silicon photodetector. The photocurrent out of one end surface was measured as the distance of the illumination position was varied along the length of the cylinder.

We have developed and tested a raytrace model [5] that uses a Monte Carlo method and can model a variety of planar LSCs. It has recently been extended to describe cylindrical LSCs and the composite structure described in this paper. A comparison between experimental and modelling results for the cylinder is shown in Figure 4.

Figure 4: Response of the output from the luminescent cylinder as a function of illumination position, measured experimentally and predicted with the raytrace model.

4 COMPUTATIONAL STUDY

4.1 Effect of the transparent bar

Using the raytrace model the experiment described in the previous section was repeated for the composite structure with the transparent material around the cylinder. A comparison between composites of three different cross-section widths and the cylinder alone is shown in Figure 5.

The presence of the transparent bar drastically improves the performance of the LSC, and even luminescence originating on the far end of the rod is guided to the detection end quite efficiently. Re-absorptions are effectively reduced as the light travels in the composite, proving the concept of this design. As expected, the output increases with bar width, but the loss in geometrical concentration ratio due to a larger PV cell area needs to be considered. In the given case, a width of 1cm appears to be a suitable choice.

Figure 5: Raytrace simulation of the effect of the transparent bar on the luminescent output. The experiment was simulated for three different cross-section widths of the bar.

4.2 Optical efficiencies and concentrations

For a concentrator system, the optical efficiency and concentration, presented in Table I for the three composite structures of different widths, are important measures. The optical efficiency is conventionally the fraction of incident light that is coupled into the PV cells.
In this calculation however, the optical efficiency is expressed as a fraction of incident light absorbed by the luminescent material. The geometrical concentration ratio is the ratio between light collection area and output area. In this case the collection area is the product of diameter of the cylinder and length of the composite, and the output area is twice the square of the bar width. The optical concentration, defined as the ratio of photon output to input, is given by the product of geometrical ratio and optical efficiency.

The optical efficiency decreases with the cross-section width, while the optical concentration increases. An appropriate width would strike the balance between achieving a high concentration to reduce area of PV cells required and yet maintaining a large enough efficiency to generate a reasonable amount of power for the given concentrator size.

Table 1: Optical efficiencies and concentrations

<table>
<thead>
<tr>
<th>Bar cross-section width</th>
<th>10mm</th>
<th>15mm</th>
<th>20mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical ratio</td>
<td>16.0</td>
<td>7.1</td>
<td>4.0</td>
</tr>
<tr>
<td>Optical efficiency</td>
<td>0.30</td>
<td>0.34</td>
<td>0.37</td>
</tr>
<tr>
<td>Optical concentration</td>
<td>4.8</td>
<td>2.4</td>
<td>1.5</td>
</tr>
</tbody>
</table>

4.3 Performance projections

Assuming partially optimised conditions, the performance of the concentrator was modelled under an AM1.5 direct solar spectrum, concentrated 50 times by the primary optics. The dimensions of the bar were modelled to be 1m in length with a cross-section of 8x8 mm² and a core diameter of 4mm. A background absorption of 0.3m⁻¹, typical for high quality polymers, was assumed for both the core and the bar. Furthermore, mirrors were placed on the two long sides of the bar and a diffuse reflector on the bottom. This allowed for incident light outside the absorption range of the dye to be partially reflected towards the PV cells. The selection of a more suitable luminescent centre, which is a crucial optimisation, was not carried out at this stage.

The projections for two different solar cells are presented here: a silicon cell and an InGaP cell. In the case of the Si cell, the overall system efficiency was 2.1%, yielding a power of 8.3W. For comparison, the cells alone, placed directly under the light, generate only a sixth of this power. Figure 6 shows the spectrum of a silicon PV cell and the spectra of the dye and the incident sunlight. One can see that the dye can absorb short wavelengths, where the cell quantum efficiency is low, and emit a red-shifted spectrum that can be converted better by the cell, thus improving the efficiency.

As the light concentration can reach several hundred suns, it is reasonable to use high-efficiency solar cells. In the case of the InGaP cell, a system efficiency of 4.6% and a power of 18.6W was predicted. However, it was found that the dye did not significantly contribute to any improvement. It can be seen in Figure 7 that the IQE of the InGaP cell is already high in the absorption region of the dye. In fact, the efficiency achieved with the mirrors alone and without the dye was only 1% (relative) smaller than the the efficiency with the dye.

It is clear that the dye was not ideal for this application. A broad absorption is required to achieve larger gains. A collection of dyes could achieve this. Our group has been investigating the use of quantum structures, such as quantum dots (QDs) and nanorods (NRs) as luminescent species [6]. These inorganic structures have a broad absorption spectrum, extending far into the UV, and a narrow emission peak. They are also inherently more photo-stable than the organic dyes.

5 CONCLUSION

A composite cylindrical luminescent concentrator has been examined for use as a secondary device for concentrated photovoltaics. Good agreement was found between experimental measurements and raytrace simulations of the cylinder. It has been shown, using the raytrace model, how luminescence can travel effectively inside the transparent bar, reducing re-absorption losses. Performance projections showed that the system has the potential to boost the power output of solar cells by several factors. However, it was found that a broad absorption range is required to make it feasible. Moreover, dyes may degrade at high concentrations while inorganic luminescent centres are expected to be more stable. By choosing suitable luminescent materials, this design may help reduce the cost of photovoltaic energy.
6 ACKNOWLEDGEMENTS

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7 REFERENCES