THE LUMINESCENT CONCENTRATOR: A BRIGHT IDEA FOR SPECTRUM CONVERSION?


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ABSTRACT: Luminescent concentrator plates with different dyes were combined with multicrystalline silicon solar cells at one side of the plate. Spectral response and IV measurements were performed. The results show an external quantum efficiency of 25% for an optical concentration factor of 10, giving an effective concentration factor of 2.5 at the absorption maximum. The electrical current of the silicon cell is increased by a factor 1.5 with respect to the bare cell under normal incidence. The influence of dye concentration, mirrored surfaces and plate dimensions on the performance of the luminescent concentrator is addressed.

Keywords: Concentrators, Light Trapping, Photoluminescence

1 INTRODUCTION

On a lab scale, state of the art photovoltaic cells reach power conversion efficiencies close to their theoretical limit. The limitations are the result of both electronic and spectral losses, of which spectral losses are the most important. For a Si solar cell this results in over 55% loss of the energy of the solar spectrum. Converting the spectrum of the incoming light such that it has a better match with the absorption spectrum of the solar cell can reduce spectral losses, especially in the case of a small absorption band, such as for dye sensitized solar cells and polymer solar cells. An interesting approach to this is the luminescent concentrator (LC).

The LC consists of a transparent matrix material, usually a flat plate, with solar cells connected to one or more sides (see figure 1). The transparent matrix contains luminescent particles such as, e.g., organic dyes or quantum dots that absorb part of the spectrum. Part of the light emitted by the luminescent particles is guided towards the solar cells by total internal reflection (ray 2 in figure 1). The LC has an important advantage over geometric concentrators. Both direct and diffuse sunlight is collected, making solar tracking unnecessary.

Ideally, the luminescence spectrum of the luminescent particles matches the spectral response of the solar cells. This can be done by, e.g., combining two infrared photons to get one photon in the visible (upconversion), or by splitting one ultraviolet photon into two visible photons (downconversion) [1]. Alternatively, different dyes can be used that cover different parts of the solar spectrum [2].

Research on LCs began in the late 1970’s. [3,4,5] Due to the lack of organic dyes exhibiting high quantum efficiency and a small overlap between absorption and emission, i.e. low reabsorption losses, the results were limited to a power conversion efficiency (η) of 4% for a stack of two LCs connected to GaAs cells [6]. Since then, organic dyes with improved stability and efficiency have come available. This, together with the availability of semiconductor quantum dots with a small overlap between absorption and emission, open up the way to LCs with better efficiencies and stabilities.

2 EXPERIMENTAL

The luminescent plates that are used in this study are made of a transparent polymer, Plexit55, of which the monomer is commercially available. The luminescent dye is added to the monomer solution and filled into moulds. Azoisobutyronitrile was used as initiator for the polymerization at a concentration of 0.05%. Homogeneous, bubble-free plates were obtained after thermal polymerization. After the plates were removed from the mould, the sides were polished to obtain good, optically flat surfaces.

Two dyes were used, Macrolux® Fluorescence Red G (FR, a Coumarin derivative, Bayer) and S13 (perylene dye, gift from Prof. H. Langhals, University of München [7]). The concentration of the dyes ranged from 0.001 wt.% up to 0.005 wt.% resulting in an absorbance between 0.55 and 2.24 for 4-5 mm thick LCs.

Flat LC plates (5x5 cm² or 5x10 cm²) were combined with multicrystalline silicon solar cells on one side of the plate (figure 1). The cells were connected using PE 399 KrystalFlex® film for LCs containing Fluorescence Red G and a two component polymethylmethacrylate (PMMA) glue for LCs containing S13. The KrystalFlex®

Figure 1: Schematic 3D view of a luminescent concentrator. AM 1.5 light is incident from the top. The light is absorbed by a luminescent particle. The luminescence from the particle is randomly emitted. Part of the emission falls within the escape cone (determined by the angel (a)) and is leaving the luminescent concentrator at the side (1). The other part of the luminescence is guided to the Si cell by total internal reflection (2).
The LCs had mirrors on the "non-connected" and bottom spectrum of Fluorescence Red (left, dash dotted line) and plates (dashed lines). Also shown is the extinction spectrum of Fluorescence Red (left, dash dotted line) and S13 (right, dash dotted line).

Figure 2: EQE spectra of Fluorescence Red (left) and S13 (right) doped LC plates. Spectra are shown for two LC dimensions: 5x5 cm² plates (solid line) and 5x10 cm² plates (dashed lines). Also shown is the extinction spectrum of Fluorescence Red (left, dash dotted line) and S13 (right, dash dotted line).

Cells were connected to the 5 cm side of the LCs. The LCs had mirrors on the "non-connected" and bottom sides. The maximum EQE for the plates with different dyes is comparable, although the absorbance differed slightly, 2.06 for FR and 1.73 for S13. As can be seen, a smaller plate results in a significantly higher EQE for both FR and S13. This indicates that absorption by the Plexiti55, and/or re-absorption by the dye, is playing an important role. The dash-dotted lines show the extinction spectra of the LCs. It is clear that the EQE spectrum is reflecting the absorption by the dye.

To study the effect of re-absorption in more detail, plates with different dye concentrations were made. The EQE spectra of all these plates was measured. Based on these spectra, the AM1.5G short circuit current density (\(J_{sc}\)) was calculated by taking the integral of the overlap between the EQE spectra and the AM1.5G spectrum at 100 mW/cm². The measured AM1.5G \(J_{sc}\) was corrected for differences in plate top area, and the \(J_{sc}\) of the bare mc-Si cell.

Figure 3 shows this corrected \(J_{sc}\) for non-mirrored plates, as a function of the LC absorbance. The results show the same, roughly linear, increase in \(J_{sc}\) with absorbance for both dyes and plate sizes. Only at an absorbance >2, the FR LC deviates from this trend. The linear increase suggests that reabsorption losses are not very large in the absorbance range studied. For S13 this was expected, as the reported luminescence quantum efficiency of this dye is \(~100\%\) [7]. So even if reabsorption is taking place, this does not result in losses. The luminescence quantum efficiency of FR is not reported but the linear results suggest that it is also high. As the lower \(J_{sc}\) of the larger plates can not be due to reabsorption losses, it must be resulting from background absorption in the host material. Background absorption is obviously higher in the larger LC since light rays have to travel longer distances to reach the Si cell. Figure 3 also shows that the calculated AM1.5G \(J_{sc}\) is much lower for S13 compared to FR, although the maximum EQEs are comparable. This is due to the smaller and more peaked absorption spectrum of S13, which results in a smaller overlap with the solar spectrum.

A small part of the emitted luminescence of the dye is guided to the mc-Si cell via total internal reflection. This means that a large part of the luminescence is
escaping via the non-connected surfaces. For a polymer matrix like Plexit55, with a refractive index of about 1.5, roughly 75% of the luminescence is lost. In order to reduce the losses, mirrors were applied on the 3 "non-connected" sides and the bottom (see figure 1). First the EQE spectrum of the LC was measured without mirrors and then mirrors were subsequently applied on the right (Ri), front (Fr) and rear (Re) side. Finally the mirrored plate was put on a stack of white, diffuse reflecting tissues and the EQE spectrum was measured. The AM1.5G Jsc was calculated based on the EQE spectra and normalized as mentioned before to correct for size differences and differences in the performance of the mc-Si cells.

The result is shown in figure 4 for both FR and S13 5x10 cm² plates. Applying the first mirror on the right (Ri, opposite to the Si cell) results in an increase in Jsc, which is expected as the escaping luminescence on the right is now redirected towards the mc-Si cell. The second mirror, on the front (Fr), gives an almost identical Jsc. The reason for this is that the reflected luminescence from this mirror can reach the opposite facet before falling upon the mc-Si cell, and thus can still escape from the plate. So the gain of this second mirror is negligible. Applying a mirror on the opposite side, the rear side, gives a slight increase in Jsc.

The fact that this increase is only small is probably due to induced losses at the interface between mirror and plate. Applying a mirror changes the refractive index difference at the interface. This results in a reduction in the reflection of the luminescence in the so-called trapped cone with respect to the 100% total internal reflection in the case without a mirror. So the increase in current due to the reflection of the otherwise escaping luminescence is apparently cancelled by the additional losses due to the mirrors. A large increase is observed when a bottom reflector is applied. The bottom reflector reflects the incoming light that is not absorbed by the dye, thereby effectively doubling the absorption. This trend in Jsc upon applying mirrors is seen for all plates, irrespective of dye concentration or plate size, which indicates that the dye concentration can be increased to get a more efficient LC.

![Image of Figure 4](image-url)

**Figure 4:** Influence of mirrored sides on the normalized current density for a 5x10 cm² S13 doped LC with an absorbance of 2.09 and a Fluorescence Red doped 5x10 cm² LC with an absorbance of 2.05.

<table>
<thead>
<tr>
<th>plate area</th>
<th>I (mA)</th>
<th>V (V)</th>
<th>FF</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bare cell</td>
<td>86</td>
<td>0.587</td>
<td>0.758</td>
<td></td>
</tr>
<tr>
<td>50 cm²</td>
<td>all mirrors</td>
<td>130</td>
<td>0.595</td>
<td>0.722</td>
</tr>
<tr>
<td>bare cell</td>
<td>85</td>
<td>0.588</td>
<td>0.756</td>
<td></td>
</tr>
<tr>
<td>25 cm²</td>
<td>all mirrors</td>
<td>93</td>
<td>0.582</td>
<td>0.708</td>
</tr>
</tbody>
</table>

**Table 1:** Results of current-voltage measurements on both bare mc-Si cells and mc-Si cells connected to a Fluorescence Red G doped LC with an absorbance of 2.05. Parameters given are: current I (mA), voltage V (V), fill factor FF and power conversion efficiency η (%).

Figure 2 shows that the highest Jsc was obtained for a FR LC with an absorbance of 2.05. IV measurements of this LC with mirrors were performed to obtain the AM1.5G 100 mW/cm² efficiency. The result is given in Table 1 for the 5x5 cm² and 5x10 cm² plate. The measured currents of the bare mc-Si cells are also given. It shows that the mc-Si cells that were used performed almost equally well. Both the 5x5 cm² and the 5x10 cm² LC have a higher current than the bare mc-Si cell. Due to its large surface area, the 5x10 cm² LC gives rise to a 1.5 times increase in current compared to the bare mc-Si cell.

4 CONCLUSIONS

The results show a drastic, 1.5 times, increase in the current of a Si cell when connected to a LC with mirrors. As the short circuit current is still increasing with dye concentration in the range that was studied, a further increase in current is expected by using higher dye concentration, and better mirrors.

In this proof of principle, the overlap between the dye absorption spectrum and the solar spectrum is small, resulting in a low overall efficiency. Improvements will come from using multiple dyes and/or quantum dots that together cover the entire solar spectrum and from using solar cells that better match the luminescence spectra. Additionally the matrix material needs to be improved to reduce absorption losses by the matrix.

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