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.
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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.
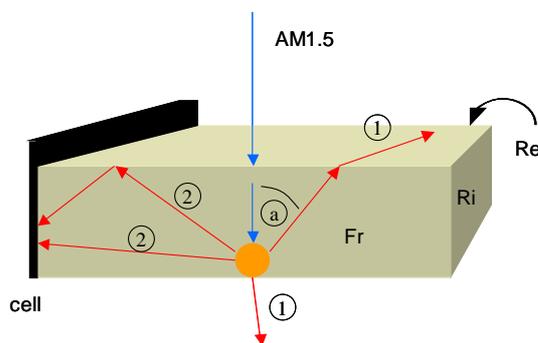
Figure 1: Schematic 3D view of a luminescent concentrator. AM 1.5 light is incident from the top. The light is absorbed by a luminescent particle. The luminescence from the particle is randomly emitted. Part of the emission falls within the escape cone (determined by the angel (a)) and is leaving the luminescent concentrator at the side (1). The other part of the luminescence is guided to the Si cell by total internal reflection (2).

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, Macrolex® 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 LC's.

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©

film was put on the Si cell and the LC was held on top of the film. The complete stack was then heated on a hotplate at 125 °C, until the KrystalFlex© film became transparent. KrystalFlex© was chosen for its refractive index of 1.49, which is similar to the refractive index of the Plexit55, thereby minimizing reflection losses at the interface between the plate and the Si cell. The two component PMMA consisted of a mixture of 18.16 gram Altuglas P10a and 0.839 gram Altuglas P10b. After mixing it was left to react for about 15 minutes. The glue was applied to the Si cell and next the LC was pressed onto the cell. The glue was dried overnight at room temperature. During handling of the LC plates, the cells that were connected using the PMMA glue became (partly) disconnected, resulting in scattering at the cell connection.

To improve the performance of the LCs, aluminium mirrors were applied to the other 3 sides of the plate. For these mirrors, adhesive 3M Scotchcal 7755 SE mirror foil, with a reflection between 87 and 95% was used. As a bottom reflector a stack of white tissues with a diffuse reflection of 86% was used.

External Quantum Efficiency (EQE) measurements were carried out using a home-built set-up, consisting of a 1000 W xenon lamp, 34 band pass interference filters and 4, 150W halogen lamps for the bias illumination. Measurements with and without bias illumination gave similar results. The reported spectra in this paper are measured without bias illumination in order to reduce the risk of unwanted reflections to couple into the LC plate. Current-voltage (IV) measurements were performed using a class A solar simulator according to the ASTM-E948 norm. [8]

3   RESULTS

Figure 2 shows the EQE spectra of LCs of 5x5 cm^2 (solid line) and 5x10 cm^2 (dashed line), doped with FR (left part) and S13 (right part).
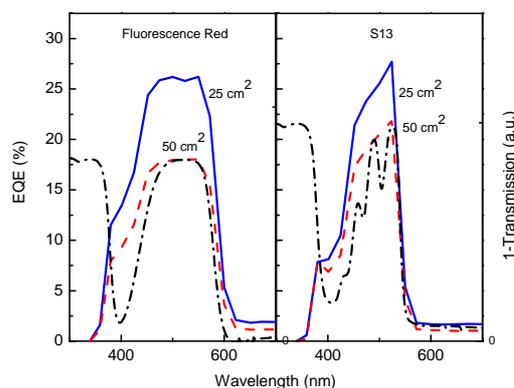

Figure 2: EQE spectra of Fluorescence Red (left) and S13 (right) doped LC plates. Spectra are shown for two LC dimensions: 5x5 cm^2 plates (solid line) and 5x10 cm^2 plates (dashed lines). Also shown is the extinction spectrum of Fluorescence Red (left, dash dotted line) and S13 (right, dash dotted line).

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 Plexit55, 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/cm^2. 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 Jsc 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.
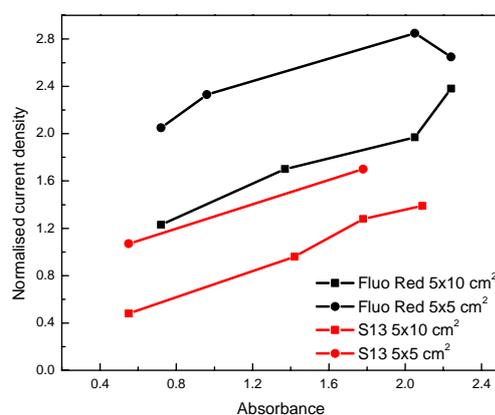

Figure 3: Corrected current density as a function of the LC absorbance for Fluorescence red and S13 doped LCs. The measured current density was corrected for the plate top area, and the bare mc-Si cell current density.

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 J_{sc} 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 cm^2 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 J_{sc}. 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 J_{sc}.
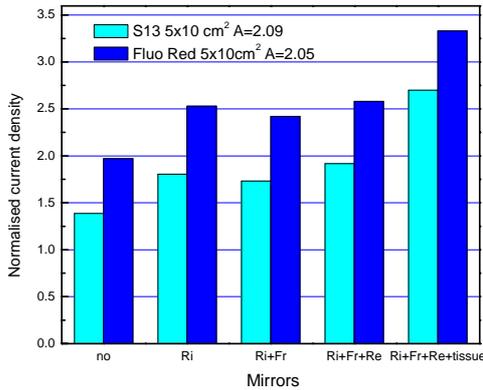
Figure 4: Influence of mirrored sides on the normalized current density for a 5x10 cm^2 S13 doped LC with an absorbance of 2.09 and a Fluorescence Red doped 5x10 cm^2 LC with an absorbance of 2.05.

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 J_{sc} 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.

plate area		*I*	*V*	*FF*	η
	bare cell	86	0.587	0.758	
50 cm^2	all mirrors	**130**	0.595	0.722	1.1
	bare cell	85	0.588	0.756	
25 cm^2	all mirrors	**93**	0.582	0.708	1.6

Table I: 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 J_{sc} 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/cm^2 efficiency. The result is given in Table I for the 5x5 cm^2 and 5x10 cm^2 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 cm^2 and the 5x10 cm^2 LC have a higher current than the bare mc-Si cell. Due to its large surface area, the 5x10 cm^2 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.

5   ACKNOWLEDGEMENTS

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