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The Luminescent Solar Concentrator (LSC) consists of a transparent polymer plate, containing luminescent particles. Solar cells are connected to one or more edges of the polymer plate. Incident light is absorbed by the luminescent particles and re-emitted. Part of the light emitted by the luminescent particles is guided towards the solar cells by total internal reflection. Since the edge area is smaller than the receiving one, this allows for concentration of sunlight without the need for solar tracking. External Quantum Efficiency (EQE) and current–voltage (I–V) measurements were performed on LSC devices with multicrystalline silicon (mc-Si) or GaAs cells attached to the sides. The best result was obtained for an LSC with four GaAs cells. The power conversion efficiency of this device, as measured at European Solar Test Installation laboratories, was 7.1% (geometrical concentration of a factor 2.5). With one GaAs cell attached to one edge only, the power efficiency was still as high as 4.6% (geometrical concentration of a factor 10). To our knowledge these efficiencies are among the highest reported for the LSC.

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1 Introduction Already in the late 70's, an interesting approach for reducing the costs of photovoltaics was proposed. This approach comprises a luminescent solar concentrator (LSC) [1–3] to concentrate incoming sunlight onto a small photovoltaic cell. In this way, a smaller solar cell can be used while maintaining the same power output.

The LSC consists of a transparent matrix material, usually a flat plate, with solar cells attached at one or more sides, see Fig. 1. The transparent matrix contains luminescent particles such as organic dyes or quantum dots that absorb part of the incident solar spectrum. Part of the light re-radiated by the luminescent particles is guided towards the solar cells by total internal reflection. Unlike geometrical concentrators, the LSC concentrates both direct and diffuse light, making expensive tracking unnecessary. As a result, its cost per unit area is expected to be much less than for the currently available photovoltaic cells.

The extensive study of Zastrow et al. [4] on the LSC in the 80's resulted in a power conversion efficiency η of 4% for a stack of two 40×40 cm^2 LSCs connected to GaAs cells. Here the power conversion efficiency is defined in the standard way, i.e. the electrical power from the solar cell divided by the power of the incident light on the top surface of the concentrator plate. Recently, Currie et al. [5] reported calculated power conversion efficiencies of 5.5% for single plate LSCs in which they used a combination of luminescent and phosphorescent materials. The few reports that mention measured power conversion efficiencies range from 2.7% (5×5 cm^2 LSC, one mc-Si cell at the side) [6] to 6.7% (2×2 cm^2 2 plate stack LSC, four InGaP cells at the sides) [7]. It is not possible to compare these efficiencies directly because the efficiency of the LSC strongly depends on the LSC dimensions, the number of attached solar cells and the use of mirrors at the sides or backside. In this paper we perform ray-tracing simulations of our best devices and compare them with experimental results for one cell attached to the LSC as well as a four cell configuration.

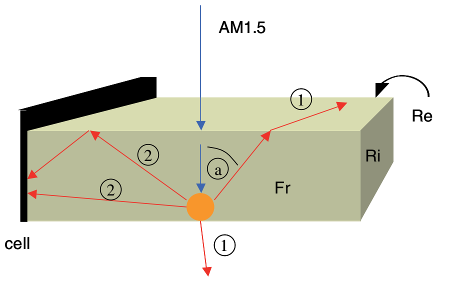

Figure 1 (online colour at: www.pss-rapid.com) Schematic 3D view of a LSC. Light is incident from the top, partly absorbed by a luminescent particle and then randomly emitted at a higher wavelength. Part of the emission falls within the escape cone (determined by the angle (a)) and is lost from the LSC at the surfaces (1). The other part is guided to the Si cell by total internal reflection (2).

2 Modelling Modelling of the LSC has improved substantially during the last decade. Two different modelling methods can be distinguished. One approach is the detailed balance model described by Chatten et al. [8, 9] and used by several other groups [10, 11]. The second method is based on ray-tracing [12–14]. Recently, we have reported on a ray-tracing model [15] that is able to simulate experimental results on single dye-doped LSCs. Contrary to the model by Gallagher, this model does not include individual quantum dots or molecules, but applies statistical averaging of the absorption. This is done in the following way. First a total absorption coefficient α_{tot} is determined by adding the absorption coefficients from the background medium and the different luminescent species. Next the distance at which absorption takes place is calculated using the inverse function of the cumulative distribution function $u(x) = (1 - \exp(-\alpha_{tot}x)$, where $u(x)$ is a uniform random number between 0 and 1. Another uniform random number between 0 and α_{tot} is drawn to determine whether the absorption is occurring in the matrix or in one of the luminescent species and if this leads to emission or not. Previously we have shown that this ray-tracing program for the LSC is able to describe our experimental results [16].

3 Results The LSC plates that have been used in this study consist of polymethylmethacrylate (PMMA), which was made by polymerising the commercially available monomer/polymer mixture Plexit 55. Two dyes were used, 0.01 wt% Lumogen F Red305 (Red305) from BASF (a perylene) and 0.003 wt%. Fluorescence Yellow CRS040 (CRS040) from Radiant Color (a coumarine). Flat LSC plates with a dimension of $5 \times 5 \times 0.5$ cm^3 were combined with 50×5 mm^2 multicrystalline silicon (mc-Si) from ECN, or GaAs or InGaP solar cells from FhG-ISE. The cells were connected using PE 399 KrystalFlex© film. To improve the performance of the LSCs, aluminium mirrors (adhesive 3M visible mirror foil, 97% reflection) were applied to the remaining three sides of the plate. At the rear side of the collector, a diffuse reflector (97% reflection) has been used. Characterization of the modules was performed at ECN and also by the European Solar Test Installation (ESTI) laboratories of the Joint Research Centre of the European Commission, sited in Ispra (Italy) [17].

Table 1 Calculated I_{sc} and efficiency η for a 5×5 cm^2 LSC containing Red305 and CRS040, connected to a mc-Si, GaAs or InGaP, using typical values for V_{oc} and FF of the solar cells.

	I_{sc} (mA) calc.	V_{oc} (V) cell	FF cell	η (%) calc.
mc-Si	162	0.6	0.76	2.9
GaAs	158	1.0	0.83	5.2
InGaP	149	1.38	0.84	6.9

The three types of cells that are used, mc-Si, GaAs and InGaP are all able to absorb the dye emission and thus the expected current from the cells, when connected to the LSC, is similar. However, the open circuit voltage V_{oc} of the cells is different due to the different optical bandgap of the semiconductors and thus the efficiency will differ when using a GaAs or InGaP cell instead of a mc-Si cell. We used the ray-tracing program to calculate the short circuit current I_{sc} for a 5×5 cm^2 LSC with the three types of attached solar cells. With these calculated I_{sc}, and measured V_{oc} and fill factor FF of the cells, the LSC device efficiencies were calculated. Table 1 gives the results. As expected, the calculated efficiency increases with the V_{oc} of the attached solar cell, from 2.9% for an LSC with a mc-Si cell to 6.9% for an LSC with an InGaP cell. As was mentioned before, the short-circuit currents from the cell are expected to be similar for the three types of cell. However, Table 1 shows that the I_{sc} decreases with increasing V_{oc}. This can be understood from the EQE measurements as shown in Fig. 2. For these measurements the same LSC plate was used for the three measurements and the solar cells were attached using microscope immersion oil in order to be able to remove the cells after the measurement.

Figure 2 shows clearly the response between 400 nm and 600 nm, resulting from the absorption of the dyes in the LSC plate. At higher wavelengths there is still a response, which is due to incident light that is scattered at the diffuse backside mirror after which it hits the solar cell.

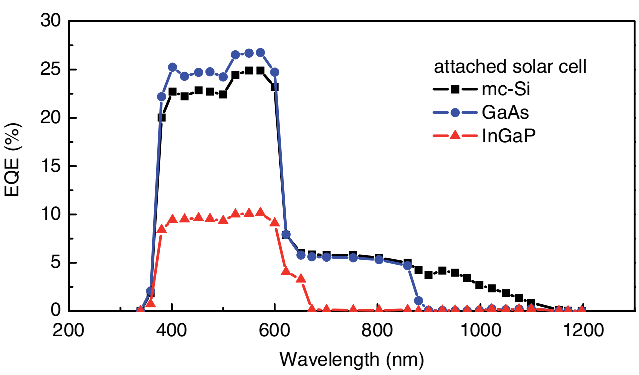

Figure 2 (online colour at: www.pss-rapid.com) EQE measurement of a LSC with mc-Si, GaAs or InGaP cell attached to the side.

Table 2 Measured solar cell parameters for a 5 × 5 cm^2 LSC containing Red305 and CRS040.

device	geometrical gain	I_{sc} (mA) LSC	V_{oc} (V) LSC	FF LSC	module η (%) LSC	measured at
1 GaAs	10	134	1.025	0.836	4.6	ECN*
cell		138	1.048	0.799	4.6	ESTI
		106±	1.038	0.801	3.5	ESTI
4 GaAs	2.5	213	0.99	0.794	6.7	ECN*
cells		220	1.008	0.795	7.1	ESTI
parallel		174±	0.997	0.768	5.3	ESTI
4 GaAs	2.5	53	4.0	0.8	6.8	ECN*
cells		53	4.04	0.811	7.0	ESTI
series		42±	3.99	0.787	5.2	ESTI

* Data measured at ECN were not corrected for the mismatch factor [17],
± measured without a diffuse backside reflector.

For this 5 × 5 cm^2 LSC plate, the contribution of this scattered light to the I_{sc} is substantial, but for larger LSC sizes it will decrease and will not make a significant contribution to the current. Furthermore, the contribution of the scattered light depends strongly on the type of solar cell that is used. Due to the relatively small bandgap of mc-Si, the scattered light contribution to the I_{sc} is rather large, but for the larger bandgap GaAs it is much less and for InGaP it is negligible. Note that the height of the EQE spectrum for the device with the InGaP cell is much lower than for the mc-Si and GaAs cell. The reason for this is that the dye emission becomes red-shifted by re-absorption processes. Thus the dye emission spectrum that reaches the solar cell is red-shifted. As a result, it will not be completely absorbed by the InGaP cell, thereby reducing the EQE of the LSC. At this moment the ray-tracing program assumes that all dye emission is absorbed by the solar cell, and thus overestimates the performance of the LSC connected to the InGaP cell. We are currently adapting the program to take this into account.

We performed current–voltage measurements on a 5 × 5 × 0.5 cm^3 LSC with these dyes and a mc-Si cell attached. This resulted in a measured I_{sc} of 147 mA, a V_{oc} of 0.58 V and a FF of 0.79, resulting in a measured efficiency of 2.7% which is very close to the calculated efficiency of 2.9% using the ray-tracing program.

Next, an LSC plate was connected to a single GaAs cell and the other edges were covered with mirrors. A second LSC plate was connected with four GaAs cells, one on each edge. EQE measurements and $I-V$ measurements with a solar simulator were performed at ECN as well as at ESTI. Results are given in Table 2. As can be seen the measurement results of ECN and ESTI are comparable. Note that the results for ECN were not corrected for the spectral mismatch factor to AM 1.5. The single-cell LSC reaches an efficiency of 4.6%, which is to our knowledge the highest reported efficiency for a single plate LSC. When four GaAs cells are attached to the sides of the LSC the efficiency ranges between 7.0% and 7.1%, depending on the interconnection of the solar cells (either series or parallel). For comparison the devices were also measured without the diffuse backside reflector and these results are also shown in Table 2. Without a backside reflector the current of an LSC with a single GaAs cell connected decreases by 32% and for four GaAs cells in parallel by 26%. This shows the importance of using a diffuse backside reflector. The measured currents of the devices are somewhat lower than expected from the ray-tracing calculations. This might be due to non optimal coupling of the solar cell with the LSC plate. There might also be some degradation of the LSC plate since it was prepared about a year before the measurements and was not kept in dark permanently.

4 Conclusions In conclusion, we showed results of referenced characterization of LSC plates with up to 7.1% efficiency. This efficiency is to our knowledge the highest one reported for LSCs. Such a result was obtained with a diffuse reflector on the rear side, which increases the measured current by 26% (single GaAs cell) and by 32% (four GaAs cells).

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