A Luminescent Solar Concentrator with thin-film amorphous silicon solar cells

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A Luminescent Solar Concentrator with thin-film amorphous silicon solar cells
A proof-of-principle experiment

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Abstract

Luminescent Solar Concentrators are a low-cost alternative photovoltaic application. They consist of a transparent plate doped with a luminescent species, to the sides of which are attached mirrors and solar cells.

In this thesis a proof-of-principle configuration of two thin-film amorphous silicon solar cells and two mirrors was built and tested. It is the first time that amorphous silicon was used. Its higher-than-crystalline-silicon band gap which reduces thermalisation losses and its low cost can be defining factors in developing a viable low-cost solar cell with applications in the built environment.

A system efficiency of 1% was measured, while higher results may be obtained under improved measurement conditions.
1 Introduction

The search for renewable energy has been going on for some decades now. Having alternatives to fossil fuels lessens countries’ dependence on oil-producers and hence provides increased reliability.

The investment in renewable energy has increased by a factor 4 in the last 4 years, with wind and solar PV capacity showing a 250 and 600% increase, respectively. Small hydropower and biomass also have a large share in the world renewable energy use, but these also have serious drawbacks: hydropower is only possible in very specific locations, while the production of biomass for energy use is limited because it competes with food production. Figure 1 shows the share of different types of renewable energy. It can be seen that solar PV still has a very small share, but as stated above its growth is rapid. [1]
There are two important reasons why solar energy has not yet attained a large market share: intermittency and cost of energy.

The intermittent nature of solar energy, meaning that it is only available at irregular and unpredictable intervals, can be worked around by using solar energy in combination with non-intermittent energy sources and by storage of energy.

The cost of solar energy is still high compared to conventional energy sources, mainly because much of the technology is still very new. It can be said that cost reduction is the main driver for research into solar energy technology.

1.2 Cost-reduction

In the very broad field of solar energy two main approaches can be defined in the quest for cost reduction:

1) Reduction of cost of components of existing solar energy systems and
2) development of cheaper new solar energy systems.

The first approach is an example of technological learning and has led to PV systems now being available on the consumer market. Even though the cost of solar energy
may still be higher than that of fossil-based electricity, consumers will still profit because the *price* of grid electricity is higher still (ofttimes helped partially by investment subsidies or feed-in tariffs).

The second approach in itself is a wide field of research that tries to reduce per-megawatt cost by increasing the intensity of the cell (heliostats, power towers etc.), by decreasing the cost of constituent materials, as in the case of for instance organic PV, or by enhancing the coupling between the absorption characteristic of the cell and the incident spectrum (tandem cells). Luminescent solar concentrators try to combine these cost-reducing paths.

![Schematic Representation of a LSC without mirrors](Figure 2)

*Figure 2 - Schematic Representation of a LSC without mirrors. Incident light that is absorbed by a luminescent particle will upon re-emission escape from the plate if it stays within the escape cone (rays 1). Otherwise total internal reflection will guide the light to the cell (rays 2). Source: [4]*

### 1.3 The luminescent solar concentrator

A luminescent solar concentrator (LSC) consists of a sheet or plate of a transparent material which is doped with a luminescent moiety and to the sides of which are attached solar cells. The bottom is covered with a mirror. The luminescent moieties absorb incident light and re-emit it at a redshifted wavelength. Due to total internal reflection most of the light is trapped inside the plate and guided to the edges, where it is absorbed by the solar cells and converted into electricity. This is shown schematically in Figure 2.
Light is concentrated onto the solar cells because the plate's thickness is small compared to its length and width, the materials cost is low, because the active surface (cheap plastic) is larger than the solar cell surface (expensive semiconductor) and the red-shifted incident light is more efficiently transformed into electricity in the solar cells. In this way the three cost-reducing paths defined above are combined in one device. Additionally, an LSC has the advantage of being able to utilize diffuse as well as direct (sun)light.

1.4 History

In their 1977 paper, Goetzberger and Greubel first proposed ‘a new principle for solar energy conversion’[5], which was, as they called it, the ‘fluorescent collector’. They identified three practical difficulties to be solved: ‘synthesis of dyes with stringent requirements, identification of plastic materials with high transparency and development of solar cells with higher band gaps.’ Mainly due to the first of these difficulties, interest for their idea waned because it became clear that the luminescent species used (dyes) had stability issues under illumination.

In recent years the subject has again gained some attention, partly due to the promise of quantum dots as luminescent species, and partly in the framework of the Fullspectrum project, which is ‘a new PV wave making more efficient use of the solar spectrum’[6].

The three difficulties foreseen by Goetzberger and Greubel have been addressed extensively in the recent past. For instance, the quality of dyes on the market today has been shown to be much higher than in was thirty years ago[7]. Secondly, transparent polymer plates have been produced with absorption loss of the order 0.5 m⁻¹[4]. Thirdly, the development of solar cells with higher band gaps has been looked into which has already led to interesting results, such as a 7.1% efficiency achieved with an LSC with four GaAs cells attached to the sides[8].

1.5 Amorphous Silicon

A new consideration is the possible use of amorphous silicon solar cells on the sides of an LSC. Amorphous silicon (a-Si) has the advantage of lower cost and higher band
gap, but a-Si cells typically have a significantly lower efficiency. This thesis tries to answer the following question:

How does an LSC system consisting of a doped PMMA plate with a-Si:H solar cells attached to it behave under illumination, how does it compare to similar systems with crystalline cells and how can it be modelled.
2 Theory

In describing the theory underlying the luminescent solar concentrator principle it is useful to follow a beam of light as it traverses the system, from its first contact with the plate to the ‘conversion’ of photons into electrons. In the following discussion light will be described both consisting of photons and as a beam, because both ways of looking at light are useful at times.

2.1 Optics

Because in an LSC light has to travel through different media, undergoing absorption and (more or less isotropic) emission, the optical properties of the system are of prime importance. Table 1 lists the loss mechanisms that limit optical efficiency with typical values, as taken from [9].

<table>
<thead>
<tr>
<th>Loss Mechanism</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission at the surface (( \eta_{tr} ))</td>
<td>0.96</td>
</tr>
<tr>
<td>Absorption efficiency (( \eta_{abs} ))</td>
<td>0.15-0.20</td>
</tr>
<tr>
<td>Internal quantum efficiency (( \eta_{qe} ))</td>
<td>0.95-1.00</td>
</tr>
<tr>
<td>Stokes efficiency (( \eta_{st} ))</td>
<td>0.85-0.95</td>
</tr>
<tr>
<td>Trapping efficiency (( \eta_{trap} ))</td>
<td>0.74</td>
</tr>
<tr>
<td>Fraction of light not escaping after absorption/re-emission (( \eta_{re} ))</td>
<td>0.5-0.8</td>
</tr>
<tr>
<td>Transparency efficiency of the plate (( \eta_{pl} ))</td>
<td>0.85-0.95</td>
</tr>
</tbody>
</table>

A beam of light, upon reaching the outer surface of the plate, is either transmitted into the plate, or reflected away from it. This *external reflection* is the first loss mechanism, denoted \( \eta_{tr} \), and it depends on the difference in refractive index of the plate and the air (or whatever medium the LSC is in contact with). It typically accounts for about 4%.

When light ‘hits’ a luminescent particle, there’s roughly a 15-20% chance of absorption taking place. This is the absorption efficiency \( \eta_{abs} \).

Absorption mostly (95-100% of the time) results in shifted re-emission. Otherwise, the energy is lost in the form of vibrations of the dye (heat). This is called the internal quantum efficiency \( \eta_{qe} \).
The Stokes efficiency $\eta_{st}$ is loss because of the Stokes shift: light is emitted at a longer wavelength than it was absorbed at (and hence has lower energy). On the one hand this energy loss is detrimental to the performance of the LSC, but on the other hand the Stokes shift is essential in coupling the re-emitted light to the solar cell spectral response and reducing re-absorption losses.

Light in the plate can only escape if it hits the top surface at an angle steeper than the critical angle (so if it comes from within the escape cone). For a flat slab with refractive index of around 1.5, this means than roughly 25% of the light will escape through the top surface [10]. This describes the trapping efficiency $\eta_{\text{trap}}$.

Because re-emission is isotropical, more light will escape through the top surface if more re-absorption takes place. $\eta_{\text{re}}$ is the fraction of light that manages to stay in the slab until absorbed.

Light travelling through the plate can be absorbed or scattered by the plate material. This effect will be small for highly transparent materials like glass and PMMA but the efficiency is not 100% and denoted by $\eta_{\text{pl}}$.

Figure 3 - Possible paths the light can take upon encountering an LSC plate. The luminescent particles are represented by circles. A number of loss mechanisms is shown. A: reflection at the top surface, B: escape through the escape cone, C: no absorption, D: re-absorption and QE $< 1$. 

![Figure 3 - Possible paths the light can take upon encountering an LSC plate. The luminescent particles are represented by circles. A number of loss mechanisms is shown. A: reflection at the top surface, B: escape through the escape cone, C: no absorption, D: re-absorption and QE $< 1$.](image-url)
Figure 3 shows schematically how the light can travel within the plate. Green arrows are desired events, while red arrows represent loss mechanisms: re-absorption and self-absorption due to a smaller-than-unity quantum efficiency (D), direct (B) and reflected (C) escape-cone loss, and reflection at the surface (A). The escape cone at any point on the top surface of the plate is the cone spanned by the critical angle: light coming from outside the escape cone will undergo total internal reflection. The optical efficiency is calculated by multiplying all the efficiencies described above:

$$\eta_{opt} = \eta_{tr} \eta_{abs} \eta_{qe} \eta_{st} \eta_{trap} \eta_{ref} \eta_{pt}.$$  

and it amounts to approximately 4-10% for typical PMMA plates [9].

### 2.2 Electronics

The purpose of the LSC, and indeed of any photovoltaic device, is to excite as many electrons as possible, given the photons from incident light. Light entering the plate of an LSC consists of photons of many different energies. However, there is only a rather narrow part of the electromagnetic spectrum from which any given solar cell can efficiently use these photons to create a current.

#### 2.2.1 Bandgap losses

Two main losses related to the band gap of the semiconductor material can be identified.

*Only photons with energy higher than the bandgap of the solar cell material are absorbed and can be converted to electrons.* This means that light of lower energy than the bandgap will not contribute to the generation of electricity. Crystalline silicon (c-Si) has a bandgap of about 1.1 eV, which corresponds to a wavelength of ~1100 nm, while amorphous silicon (a-Si), which has a 1.7 eV bandgap, needs shorter wavelength light (750 nm) to excite electrons. This means that a significant amount of photons that would be absorbed by c-Si cells is lost when a-Si cells are used. See Figure 4 for a graphical representation of the a-Si and c-Si band gaps in relation to the solar spectrum [3].
Excess energy is lost: even photons with energy more than twice the band gap can only excite one electron. If an electron is excited by a photon with energy higher than the band gap, it will fall back to the conduction edge after a very short time, releasing its energy in the form of heat (a process called lattice thermalisation). Losses of this kind are lower in a-Si than in c-Si cells because of the higher band gap and the shape of the solar spectrum.

2.2.2 The Diode equation and solar cell efficiency

A solar cell is a diode: above a certain voltage threshold, current flows. Below the threshold the current is low. This can be described with the so-called ‘diode equation’:

\[ J = J_s \left( e^{\frac{qV}{k_B T}} - 1 \right), \]

with \( J_s \) the saturation current (current at low voltage), \( q \) the electron charge, \( V \) the voltage, \( k_B \) the Boltzmann constant and \( T \) the temperature. See for instance [11] for a more detailed discussion.

Figure 4 - Solar Spectrum (black), with solar spectrum at ground level (red). Added are absorption edges of a-Si and c-Si. AM0 is the solar spectrum at the top of the atmosphere, while AM 1.5 is the spectrum of sunlight that has travelled through 1.5 times the atmosphere (i.e. at sea level when the sun makes an angle of about 48° with the zenith). AM 1.5 is a good measure for sunlight at Northwestern European latitude. Source: [3]
For any solar cell, efficiency $\eta$ is defined as:

$$\eta = \frac{V_{\text{OC}} \cdot J_{\text{SC}} \cdot FF}{E \cdot A},$$

with $V_{\text{OC}}$ and $J_{\text{SC}}$ the open circuit voltage (voltage at $J = 0$) and short circuit current (current at $V = 0$), respectively, $FF$ the fill factor, $E$ the intensity of incident light ($\text{W/m}^2$) and $A$ the active area of the device. From this it is clear that high values of $V_{\text{OC}}$, $J_{\text{SC}}$ and $FF$ are desired for a solar cell with a high efficiency.

![Figure 5 - Solar cell internal quantum efficiencies for three types of solar cells. Source: [2].](image)

### 2.2.3 Solar Cell Quantum Efficiency

Solar cell internal quantum efficiency is the number of electrons excited per incident photon. This is not a constant value over the electromagnetic spectrum. The efficiency of a solar cell can be dramatically improved if only light of a favorable wavelength is used. The LSC utilizes this effect by trying to match the emission peak of the luminescent species with the optimum absorption wavelength of the cell. The shape of the spectral response curve also depends on other factors than the material, like the thickness of the cell and the nature of the front- and back contacts etc. [12]. Figure 5 shows typical spectral response curves for both an a-Si and a c-Si cell.
2.2.4 Thin film solar cells

Thin film amorphous silicon solar cells mainly consist of three layers of silicon: a so-called intrinsic layer sandwiched in-between a very thin n-doped layer and a thin p-doped layer. Figure 6 shows a schematic example of a thin-film a-Si cell. Cells are made by depositing consecutive layers on a substrate (the glass is the hindmost layer) or superstrate (glass is the topmost layer), depending on device requirements. In addition to the silicon, front and back contacts need to be added, as well as an anti-reflecting layer at the backside. The p- and n- layers are needed to generate an electric field over the intrinsic region. When electrons and holes in the intrinsic region are excited by incident photons, they are driven to their respective contacts by the electric field. This is necessary because diffusion is not sufficient due to the high defect density in an amorphous silicon layer.

See [13] for a detailed discussion of thin-film cell theory.

![Diagram of a thin-film cell](image)

*Figure 6 - Basic schematic representation of a thin-film cell. Light enters from the left and encounters, in order, the glass superstrate, a TCO (transparent conductive oxide), the p-i-n layers and a back contact, which is made of silver in this case. Source:[2].*

2.3 Intensity effect

The intensity of light incident on the solar cell influences the efficiency. The nature of this relation depends on the type of solar cell and the wavelength of the light. Recent research into small concentration effects (concentration factor 5-10) has
shown a decrease in FF and hence efficiency with increasing efficiency [14]. However, since at these intensities the $J_{sc}$ scales linearly with intensity the power output of a cell with concentrated incident light will still be higher than a cell without concentration.
3 Experiment

As a proof-of-principle experiment a luminescent solar concentrator was created using a dye-doped PMMA plate and two a-Si solar cells attached to opposite sides. Assembling of the device occurred at Imperial College, London. The device was then tested under a white-light source, and system efficiencies were calculated.

3.1 Materials

3.1.1 PMMA plate and luminescent species

The plastic plate used was a slab of commercially available Lucite 4T56, a PMMA doped with dyes. It is also called ‘Mars Red’, which is an appropriate name, as seen in Figure 9 (right). It was cut to dimensions 50.5 x 50.5 x 4.63 cm³. The sides were polished afterwards, to facilitate the attaching of cells and mirror foil.

Absorption and emission characteristics were measured and are shown in Figure 7. The flat absorption profile indicates a mixture of dyes, but because of the

![Figure 7 - Absorption and emission profile of the PMMA plate used in the LSC. Also plotted is the spectral response of a thin-film a-Si cell.](image-url)
commercial nature of the product it was not possible to learn from the manufacturer
the exact nature of the luminescent species in the plate.

It may be possible to find out the comprising dyes by dissolving the plate, and this
will yield a better understanding of the system as described in this work, but for
future research it is probably easier to fabricate a plate ‘from scratch’ with well
known optical characteristics. Ways of doping PMMA with luminescent species can
be found in [4].

The collection efficiency of the plate (the number of re-emitted photons that would
reach a solar cell per photon entering from the top) was determined. First, the light
intensity at the top surface and coming from the side of the plate was measured
under illumination from the white-light source at IC (see Appendix A for details of
the light-source) Appendix A and with use of an Ocean Optics HR4000 fiber optics spectrometer.

The spectrometer is positioned facing the white-light source and the spectrum is
measured. Then, the PMMA plate is positioned at an equal distance from the light-
source and the spectrometer is positioned against one side of the plate, with the
three other sides are covered with mirrors. Again, the spectrum is measured.

The result of this collection efficiency measurement is a spectrum in arbitrary units.
This was scaled by measurements from a Siemens BPW 34 reference photodiode
(area 2.56 mm²) in the same configuration. The resulting spectra are plotted in Figure
8.

The left graph shows the photon flux (units: photons/m²/s/nm), which shows that in
the emission region of the dyes (compare Figure 7) the photon flux coming through
the open side of the plate is concentrated compared to the incident photon flux at
the top surface.

The right graph shows the photon rate (units: photons/s/nm), the number of photons
entering through the top and leaving the open side of the plate per second. Here the
story is different: even at the peak emission wavelength (around 630 nm) less
photons are emitted through the side of the plate than enter the plate from above.
Another way of calculating the collection efficiency is taking the ratio of the surfaces under the right graphs.

It should be noted that during these measurements to determine collection efficiency the set-up of the system is slightly different from the main set-up: in this case there is one ‘open’ side and three mirrors, while the LSC system consists of two facing ‘open’ sides (covered with solar cells) and two mirrors. It may be that more photons escape through the top surface in this set-up due to a longer mean path length. This warrants closer study, for instance through modelling.

Values found were 693 and 321 W/m², respectively. Now, the collection efficiency CE is

\[
CE = \frac{E_S \cdot A_S}{E_T \cdot A_T},
\]
where $E_s$ and $E_t$ are the light intensities, and $A_s$ and $A_t$ are the areas of the side and top of the plate, respectively. The collection efficiency, as calculated with the values above, is 9.5%. This value is quite low because

a) only a small part of the electromagnetic spectrum is absorbed and re-emitted by the dyes, and

b) a significant amount of light escapes through the top surface. This was not measured, but simulated at IC using Monte-Carlo techniques [15].

See AAppendix B for more details of the collection efficiency measurements.

### 3.1.2 Bottom and side mirrors

To prevent light from leaving the plate other than through the solar cells, mirrors are attached to sides of the plate that are not covered with cells and on the bottom of the plate. Much of the light that reaches a mirror-covered side of the plate will not escape, due to total internal reflection. To be sure that the mirror only operates on light that would otherwise have escaped, the mirror should not be index matched to the plate, or a small layer of air should be kept between plate and mirror.

In the experiment described two of the sides of the LSC system were covered with cells. The other two sides were covered with 3M mirror foil. This has a 97% reflectivity in the visible region of the electromagnetic spectrum.

The bottom of the plate rested on a PTFE Lambertian standard reflector with broadband reflectivity of 98%, again in the visible spectrum.

Both mirror materials were not index matched to the PMMA plate.

### 3.1.3 Solar Cells

The solar cells attached to two sides of the plate are thin-film hydrogenated amorphous silicon solar cells. They were deposited at the Debye Institute for Nanomaterials Science at Utrecht University. The desired shape and size were achieved using a mask. Figure 7 also shows the spectral response of this kind of thin-film a-Si solar cells. Information on the light-sources used can be found in AAppendix A. Deposition conditions are described in A
Appendix C and cell measurements in Appendix D.

### 3.2 Construction

The plate was bonded to the cells using Krystalflex PE399 thermosoftening film, available commercially from Huntsman Polyurethane. The film has a thickness of about half a millimeter.

First, an area of Krystalflex of the size of the side of the plate was cut out and placed onto the glass cell substrate, which in turn rested on a hotplate (Figure 9, left). The hotplate was turned on and the cell with the Krystalflex was heated to 130°C and kept at that temperature for between 2 and 4 minutes to allow the Krystalflex to soften.

![Figure 9 - Photographs of the construction of the LSC system. (Left) shows the Krystalflex covering the cell, heated on a hotplate. (Right) shows the connection of the second cell on the opposite side of the first.](image)

When softened sufficiently one side of the PMMA plate was manually pressed onto the film, with the pressure being applied for a full minute to ensure a good optical contact. Thereafter the LSC system was allowed to cool down: this caused the Krystalflex to harden, firmly bonding cell and plate. In cooled state the Krystalflex still made good physical and optical contact between cell and plate. It is important to
note here that Krystalflex has a refractive index of 1.49, which is close to the values of PMMA and glass. This ensures good transmission from the plate into the cell.

The second cell was attached similarly (Figure 9, right).

For a discussion on the degradation of the cells by the bonding process see Appendix E.

3.3 Results

After the construction of the LSC-system its performance was characterized with I-V measurements. Values were obtained for the individual cells and for the cells connected in series and parallel. Results are given in Figure 10 (left) and Table 2 (left) lists some important characteristics. The measurements were performed at Imperial College, London. For cell 2, values are also given before and after bonding. This is done in Figure 10 (right) and Table 2 (right). Notice that the left graph shows current density, in mA/cm², while in the right graph it is current. This is because the active area of the LSC system is different from the active area of the solar cell which means current density comparison is not meaningful.

Table 2 - Experimental results. (Left) shows the characteristics of the bonded system. (Right) shows the difference in cell performance before and after bonding.

<table>
<thead>
<tr>
<th>The bonded system</th>
<th>Comparing cell 2 before and after the bonding process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voc (V)</td>
<td>Jsc (mA/cm²)</td>
</tr>
<tr>
<td>Cell 1</td>
<td>0.70</td>
</tr>
<tr>
<td>Cell 2</td>
<td>0.74</td>
</tr>
<tr>
<td>Parallel</td>
<td>0.72</td>
</tr>
<tr>
<td>Series</td>
<td>1.44</td>
</tr>
</tbody>
</table>
3.4 Observations on the results

From these results, the following observations can be made.

3.4.1 Individual cell performance

Cell 1 has a notably lower performance than cell 2. The $J_{sc}$ and $V_{oc}$ are of similar order, but the fill factor is much lower. This is much less apparent in the measurements made at IC prior to the bonding (see Figure 15 in Appendix D). This may be caused by mechanical damage due to measuring and handling. If so, it is something that should be watched out for in future measurements. See Appendix E for a discussion on the deterioration of the cells due to handling.

3.4.2 Connected performance

Current and voltage add in series and parallel connections, respectively. There is some irregularity in the high voltage region of the parallel measurement, but for the most part the result is as expected. The low fill-factor of cell 1 clearly has a detrimental effect on the characteristics of the connected systems.

Figure 10 - Experimental results. (Left) shows the I-V curves of the cells in the bonded system. (Right) shows the difference in cell performance before and after bonding.
3.4.3 Effect of bonding on cell performance
Looking at the right sides of Figure 10 and Table 2 we see that the short circuit current has decreased 19% and the fill factor has gone up with 18%. The value for the cell efficiency when attached to the plate is much lower because the active area is included in the definition of solar cell efficiency.

3.4.4 Solar cell internal quantum efficiency
The luminescent solar concentrator focuses light incident on the 50.5 \times 50.5 (~2550) cm$^2$ top surface of the plate onto two 50.5 \times 4.63 cm$^2$ solar cells, a total surface of 468 cm$^2$. This is a concentration factor of 5.5. This, combined with a 9.5% collection efficiency leads to an expected performance (which translates directly into a loss in short-circuit current) of $5.5 \times 9.5 \approx 52\%$ of the initial cell.

The fact that the short-circuit current 'only' decreases with 19% can be attributed to the higher-than-average internal quantum efficiency at the re-emission wavelength.

This clearly shows the advantage of the LSC, which can with modest means achieve respectable efficiencies due to a combination of concentration and spectral matching.

Reported efficiencies for LSC systems with crystalline silicon cells are of the order of 2.5% for systems with only one cell attached [4], [8].
4 Modelling

A raytrace model was developed at ECN to describe the behaviour of light within the LSC [16]. It uses statistical averaging to determine what will happen to a ray of light when it encounters an interface between two materials or a luminescent particle.

The model can be used either to predict what the performance of an LSC-system will be, given certain parameters (i.e. properties of the luminescent species, the plate, the cells and the mirrors, as well as the geometry of the system), or to estimate those parameters by iteratively changing the parameters until the simulation outcome matches experimental results.

Because the properties of the PMMA plate used in the experiment are unknown the raytrace model was used to try to estimate them.

The luminescent species were represented by one ‘down-converter’ which possessed the absorption and emission behaviour depicted in Figure 7. A quantum efficiency (the amount of re-emitted photons per absorbed photon) and a concentration were estimated.

However, this approach was unsuccessful due to the fact that multiple dyes are used, all of which in unknown concentrations and with uncertain quantum efficiency. To accurately model the system it is not possible to represent the luminescent species by just one down-converter: since both concentration and quantum efficiency differ from species to species.

A[Error! Reference source not found.] shows the input file of the model, together with commentary that may be of use in future modelling.
5 Outlook

5.1 Tuning of band gap and emission peak

One of the *raisons d’être* of the LSC is the fact that the solar cells are use more efficiently because the emission of the luminescent species occurs at a wavelength for which the cell has a high internal quantum efficiency. The data in Figure 11, which was presented earlier, is repeated here for emphasis. From the data, it can be seen that the peaks of the cell spectral response and the dye emission do not (yet) overlap as well as could be.

![Graph showing cell QE and normalised LSC absorption and emission profiles](image)

*Figure 11 - α-Si spectral response and Lucite dye emission peak*

This overlap can be accomplished either by changing the spectral response peak, which basically means using a different band gap, or by changing the dye (mixture) in the plate.
The band gap of thin-film amorphous silicon is variable to a certain extent (XXX – Wilfried, a range would be nice here. Do you have something like that?) by varying the pressure, the temperature or the deposition rate of the deposition.

Changing the concentration and/or type of the luminescent species may be an easier way to get a spectral match.

5.2 Quantum Dots

As mentioned briefly in paragraph 1.4, quantum dots are promising as a luminescent species.

Quantum dots are man-made nanoparticles. Because they have dimensions of the order of the De Broglie wavelength of the electron (10-500 nm), quantum dots can ‘trap’ electrons, much like atoms. For this reason, quantum dots are sometimes referred to as ‘artificial atoms’[17]. They can absorb and re-emit light. Typical absorption and emission spectra are shown in Figure 12.

![Figure 12](image-url) - (Left) Schematic representation of Type I and Type II quantum dots. (Right) Normalised absorption and emission spectra of Type I and Type II quantum dots. Source: C. de Mello Donega, personal communication.
Advantages of quantum dots are that they have a high stability, a broad absorption spectrum and a band gap that is tunable simply by changing their size.

On the other hand, problems arise from diffusing quantum dots into a PMMA-like material. Also, the quantum efficiency of quantum dots is noticeably lower than that of commercially available dyes.

5.3 Modelling Outlook
In [18], [19] and [16], a.o., the software referred to in chapter 4 has already been put to good use. Several other questions may be answered using the ray-trace software. Some of those are listed below.

5.3.1 Dye/QD Concentration effect on emission profile
A balance needs to be found for the concentration of the luminescent species. On one hand, the higher the concentration, the smaller the fraction of incident light that is not absorbed. On the other hand, higher concentration also means more re-absorption, which is bad for performance.

For this to be modelled, the absorption and emission characteristics of the luminescent species need to be well known. For systems with multiple dyes, like the Lucite plate from the experiment described in chapter 0, this is very difficult due to the cascading emission-absorption ‘chain’.

For systems with one luminescent species, the effect of concentration can easily be studied, and an optimum found.

5.3.2 Cell/mirror configuration
Just as for the concentration of a luminescent species, the ray-trace model can be used to see the effect of attaching more or less solar cells to the sides of a plate. Using more plates will decrease the path length of re-emitted light, and thus increase the yield, but at higher material cost. Whether the added electrical output is worth the extra cells is a question that might be answered by modelling.
5.4 Light source

Usually, solar cells are tested under so-called Standard Test Conditions (STC), which means at a module temperature of 25°C and illuminated by an AM1.5 spectrum with irradiance of 1000 W/m².

In the experiment described in chapter 0, most of the tests were performed under illumination by a light source that differed considerably in both irradiance (693 W/m²) and spectrum (see Figure 13). This means that the results obtained should not unthinkingly be compared with other experimental results.

5.5 Suggestions for follow-up experiments

The experiment described in this thesis, together with the start made with the modelling (which unfortunately did not lead to experimental insights) helped suggest the direction that future research could take.

To get useful predictions from the modelling software, well-known material and optical properties of the LSC-components are essential. The nature and concentration of the luminescent species need to be known if the modelling is to have any statistical significance. To this end, the plate used should not contain many different luminescent species (because this introduces complicated interactions that the model can not deal with, even though in the case of dyes it widens the absorption band (see Figure 7)).

Secondly, as became apparent in the measurement of I-V curves, the solar cells are quite susceptible to deterioration when handled roughly. Crocodile clamps should be avoided and the bonding process should be executed with care. If alternatives to hotplate-heating are available, they should be used. The efficiency decrease of cell 1 due to handling was 44% (See AAppendix E) so the overall efficiency of the system can be upped considerably simply by being more careful during the experiment.
6 Conclusions

A proof-of-principle luminescent solar concentrator was built and its behaviour measured.

The system consists of a polymethylmethacrylate plate measuring 50.5 x 50.5 x 4.63 cm$^3$, doped with an unknown mixture of dyes which absorb incident light and re-emit it in a narrow wavelength range: 580-630 nm. Two opposite sides of the plate are covered with thin-film amorphous silicon solar cells which have a high quantum efficiency in the wavelength range 500-700 nm. Total internal reflection and mirrors attached to the other sides and the bottom guide the re-emitted light to the cells, where it is converted into electricity.

Efficiency of the system is shown in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>Voc (V)</th>
<th>Jsc (mA/cm$^2$)</th>
<th>FF</th>
<th>η</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1</td>
<td>0.70</td>
<td>0.84</td>
<td>0.43</td>
<td>0.37%</td>
</tr>
<tr>
<td>Cell 2</td>
<td>0.74</td>
<td>1.05</td>
<td>0.66</td>
<td>0.74%</td>
</tr>
<tr>
<td>Parallel</td>
<td>0.72</td>
<td>1.82</td>
<td>0.48</td>
<td>0.91%</td>
</tr>
<tr>
<td>Series</td>
<td>1.44</td>
<td>0.97</td>
<td>0.40</td>
<td>0.79%</td>
</tr>
</tbody>
</table>

A system efficiency of almost 1% was achieved when the cells were connected in a parallel connection.

Cell 1 was damaged during the bonding process, causing the overall efficiency to be quite low. From the value for cell 2, it seems reasonable to assume that without cell damaging an efficiency of 1.5% is achievable.

Given well known materials, the ray-trace modeling software developed by ECN can be of use in predicting performance of LSC systems of different design. Because the commercially available PMMA plate used in this experiment had unknown dye properties the software could not be used in a helpful manner.
Appendix A – Light Sources

The solar cells were characterised by measuring their I-V behaviour, as well as their spectral response. I-V measurements were performed both in Utrecht (UU) and at Imperial College, London (IC), but using white-light sources of a different spectrum (the UU source being much closer in lineshape to the solar AM1.5 spectrum).

The light-source at IC was a Steuernagel Lichttechnik solar simulator with an Osram HMI 575W/SE discharge tube.

The light-source at UU is a WACOM WXS-140.

The spectra of the two light-sources, as well as the AM1.5 spectrum are shown in Figure 13 for the wavelength range 300-800 nm.
Although many of the measurements have been done both at UU and IC, the determining of the absorption and emission profile of the PMMA plate were performed at IC alone. The much higher intensity in the 400-470 nm range may have had influence on the results of these measurements.
Appendix B – Deposition

The standard cell deposition at the Debye Institute for nanomaterials science involves the deposition of layers in the following order:

**Substrate**: glass, coated with ~1 µm U-type SnO:F, manufactured by Asahi using atmospheric pressure chemical vapor deposition (APCVD).

**p-i-n structure**: using plasma-enhanced chemical vapor deposition (PECVD) at a 13.56 MHz frequency.

**p-layer**: a-SiC:H, doped with Boron. Thickness: 1.5 nm.

**i-layer**: a-Si:H. Thickness: 500 nm.

**n-layer**: a-Si:H, doped with Phosphorus. Thickness: 20 nm.

**Back reflector**: Silver, applied using physical vapor deposition. Thickness: 200 nm.

The mask used produced four glass plates, each holding 2 large cells and 2 small ones (which are used to check for defects). Figure 14 shows the result of one such
deposition. Two deposition runs were performed, because in the first run the mask caused short-circuiting between the front and back contacts. Some of the cells were OK, but a number did not work at all. A new mask was made for the second run.

All cells were taken to IC, and the best cells were chosen for connection to the plate, based on optical inspection and I-V characteristics measured at UU. In transport and handling, many of the cells were damaged in some way, which accounts for the lower performance of one of the cells used.

Because no equipment was available to cut the desired parts from the glass, in both cases the entire superstrate was bonded to the plate.
Appendix C – Cell measurements

The performance of the cells was determined. Good indicators for the performance of the cell are the I-V curve (current-voltage) and the spectral response curve. The I-V curve is made by measuring the current flowing through a cell while varying the voltage. A good solar cell shows diodic behaviour. A spectral response curve shows the internal quantum efficiency at each wavelength.

Current-Voltage behaviour

I-V measurements were performed both at Utrecht University (UU) and Imperial College London (IC). At UU this measurement was done in a pre-designed set-up used for specifically this purpose. The set-up uses conducting probes that can be connected to the front and back contacts of the cell. At IC, no such set-up was available, and crocodile clamps were used to attach the cell to the measuring device. This may have had an influence on the performance of the cells. See Appendix E.

Results of the measurements performed at UU are given in Table 4.

<table>
<thead>
<tr>
<th>Name</th>
<th>$J_{SC}$</th>
<th>$V_{OC}$</th>
<th>$V_{MPP}$</th>
<th>$J_{MPP}$</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12A</td>
<td>81.0</td>
<td>0.800</td>
<td>0.512</td>
<td>0.580</td>
<td>57.2</td>
</tr>
<tr>
<td>12B</td>
<td>82.8</td>
<td>0.797</td>
<td>0.497</td>
<td>0.560</td>
<td>58.6</td>
</tr>
<tr>
<td>13A</td>
<td>36.2</td>
<td>0.795</td>
<td>0.604</td>
<td>0.630</td>
<td>27.6</td>
</tr>
<tr>
<td>14A</td>
<td>68.5</td>
<td>0.795</td>
<td>0.444</td>
<td>0.580</td>
<td>41.7</td>
</tr>
<tr>
<td>14B</td>
<td>70.9</td>
<td>0.786</td>
<td>0.405</td>
<td>0.530</td>
<td>42.6</td>
</tr>
<tr>
<td>21A</td>
<td>41.9</td>
<td>0.800</td>
<td>0.667</td>
<td>0.63</td>
<td>35.5</td>
</tr>
<tr>
<td>21B</td>
<td>39.7</td>
<td>0.803</td>
<td>0.674</td>
<td>0.64</td>
<td>33.6</td>
</tr>
<tr>
<td>22A</td>
<td>41.9</td>
<td>0.803</td>
<td>0.665</td>
<td>0.63</td>
<td>35.5</td>
</tr>
<tr>
<td>22B</td>
<td>39.7</td>
<td>0.803</td>
<td>0.674</td>
<td>0.64</td>
<td>33.6</td>
</tr>
<tr>
<td>23A</td>
<td>41.9</td>
<td>0.803</td>
<td>0.665</td>
<td>0.63</td>
<td>35.5</td>
</tr>
<tr>
<td>23B</td>
<td>39.7</td>
<td>0.803</td>
<td>0.674</td>
<td>0.64</td>
<td>33.6</td>
</tr>
</tbody>
</table>

As stated in Appendix B two runs were performed, each with 4 plates containing 2 large cells. The first column in Table 4 shows the batch number, the plate number and the cell indicator (A or B). Some cells were measured multiple times, with the best result presented in the table. Cells 13A and 14A were used for bonding, and are
denoted in this thesis as Cell 1 and Cell 2, respectively. From the table it would appear that all the cells from the second deposition run have a better performance than cell 13A, but all of these showed severe degradation after transport to London and could not be used.

To facilitate comparison between the two measurement setups, Figure 15 shows the I-V curves of cells 1 and 2 as measured both at UU and IC. There are several things to note.

First of all, cell 2, as measured at Utrecht, has a much higher short-circuit current than cell 1, but a worse fill factor. The efficiencies of cell 1 and 2 are (UU values) 6.33 and 9.72%, respectively. From the measurements of other cells at UU, it appears that in fact most of the cells have an I-V curve similar to cell 2, and that cell 1 is something of an exception. It is unfortunate that cell 1 was one of the few cells that survived the journey to London and subsequent handling more or less intact.

Secondly, it is highly puzzling that this difference has all but disappeared in the IC measurements.

*Figure 15 - The I-V measurements of the solar cells used. Performed both at Utrecht University (UU) and at Imperial College London (IC).*
Spectral Response (Internal Quantum Efficiency)

Another important characteristic of solar cells is the spectral response: the efficiency of the photon-to-electron conversion process as a function of wavelength of incident light. The spectral response of the solar cells in question was measured at UU with a set-up used specifically for this purpose, with a monochromator that ‘travels’ through the electromagnetic spectrum through the 350-950 nm range at 10 nm intervals. The spectral response data for cells 1 and 2 is not available, but data for another cell from the same deposition is shown in Figure 16: this can, for most intents and purposes, be said to behave identically.

Figure 16 - The spectral response of a thin-film a-Si cell from the same deposition run as the cells used in the LSC.
Appendix D – Cell degradation

The bonding process involves heating of the solar cells on a hotplate and rather rough handling. Also, the measuring equipment at IC (crocodile clamps) may have caused damage that influenced cell performance.

![Graph showing I-V measurements before and after heating.](image)

*Figure 17 - Cell 1 before and after the heating process.*
*Measured at IC.*

For Cell 1, I-V measurements were performed before and after heating. The result is presented in Figure 17. The deterioration of the cell is clearly visible: the Fill Factor decreases from 0.61 to 0.38 and efficiency from 7.3 to 4.1%. Because the fill factor usually increases if a cell is heated (cf. Table 2, right) due to a higher shunt resistance it is safe to assume that the deterioration of the cell is due to handling.

The set-up of the IC measurements is shown in Figure 18, with the crocodile clamp clearly visible. Using a system like the one at UU will hopefully reduce cell deterioration due to handling.
Figure 18- Set-up of the I-V measurement. The light-source is positioned directly above the LSC. The LSC is connected to a voltage-source by a crocodile clamp and a probe. The diffuse mirror is visible underneath the PMMA plate.
## Appendix E – Model Input File

The model developed by ECN uses an input file where properties of the system are defined. That input file is described here. Many of these values can later be changed from within the graphical user interface (GUI) of the model.

<table>
<thead>
<tr>
<th>Description</th>
<th>Code Snippet</th>
</tr>
</thead>
<tbody>
<tr>
<td>The folder where the input file is located.</td>
<td>indexpath [File Folder]</td>
</tr>
<tr>
<td>Ambient Temperature (in K)</td>
<td>Temperature 300</td>
</tr>
<tr>
<td>Description of the surrounding medium</td>
<td>begin medium name air begin physics refrac 1 alpha_background 0. end physics end medium</td>
</tr>
<tr>
<td>refractive index</td>
<td>begin medium name Lucite-with-dyes begin physics refrac ./Lucite-refractive-index.idx (.) alpha_background 1 begin down_converter name Lucite-with-dyes extra_cross ./Lucite_Abs_1e25.cross Qe 0.95 N 1e25 emis ./Lucite_Emis.dat end down_converter end physics end medium</td>
</tr>
<tr>
<td>Description of the PMMA material</td>
<td>begin lightsource name light_source medium air angle 0 azimuth -1 interface block00_hig_y power 1000 phot_ev 2.32483 type spectrum spectrum ./am15g10nm.spec end lightsource</td>
</tr>
<tr>
<td>Description of the light source</td>
<td>begin block name block00 p_start 0 -0.00463 0 p_end 0.05 0 0.05</td>
</tr>
<tr>
<td>Description of the PMMA plate</td>
<td>Description of the light source</td>
</tr>
<tr>
<td>Depth of the plate</td>
<td>Length and width of the plate</td>
</tr>
<tr>
<td>Direction of incident light</td>
<td>Face of plate under illumination</td>
</tr>
<tr>
<td>Face of plate under illumination</td>
<td>Intensity</td>
</tr>
<tr>
<td>Intensity</td>
<td>Average photon energy</td>
</tr>
<tr>
<td>Average photon energy</td>
<td>Reading the spectrum from a file</td>
</tr>
<tr>
<td>begin interface_low_x</td>
<td>Description of the low-X interface (a solar cell)</td>
</tr>
<tr>
<td>-----------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>name block00_low_x</td>
<td></td>
</tr>
<tr>
<td>left_medium Lucite-with-dyes</td>
<td></td>
</tr>
<tr>
<td>right_medium air</td>
<td></td>
</tr>
<tr>
<td>begin optics</td>
<td></td>
</tr>
<tr>
<td>type reflec_fixed</td>
<td></td>
</tr>
<tr>
<td>reflec_name ./PV-plexiglass.refl</td>
<td></td>
</tr>
<tr>
<td>reflec_iqe_name ./SpecResPhotoNoBias.iqe</td>
<td></td>
</tr>
<tr>
<td>end optics</td>
<td></td>
</tr>
<tr>
<td>mirror_status gap_mirror_none</td>
<td></td>
</tr>
<tr>
<td>end interface_low_x</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>begin optics</th>
<th>Reading reflectivity data from a file</th>
</tr>
</thead>
<tbody>
<tr>
<td>reflec_iqe_name ./SpecResPhotoNoBias.iqe</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>begin interface_hig_x</th>
<th>Description of the high-X interface (a solar cell)</th>
</tr>
</thead>
<tbody>
<tr>
<td>name block00_hig_x</td>
<td></td>
</tr>
<tr>
<td>left_medium Lucite-with-dyes</td>
<td></td>
</tr>
<tr>
<td>right_medium air</td>
<td></td>
</tr>
<tr>
<td>begin optics</td>
<td></td>
</tr>
<tr>
<td>type reflec_fixed</td>
<td></td>
</tr>
<tr>
<td>reflec_name ./PV-plexiglass.refl</td>
<td></td>
</tr>
<tr>
<td>reflec_iqe_name ./SpecResPhotoNoBias.iqe</td>
<td></td>
</tr>
<tr>
<td>end optics</td>
<td></td>
</tr>
<tr>
<td>mirror_status gap_mirror_none</td>
<td></td>
</tr>
<tr>
<td>end interface_hig_x</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>begin interface_low_y</th>
<th>Description of the low-Y interface (diffuse mirror)</th>
</tr>
</thead>
<tbody>
<tr>
<td>name block00_low_y</td>
<td></td>
</tr>
<tr>
<td>left_medium Lucite-with-dyes</td>
<td></td>
</tr>
<tr>
<td>right_medium air</td>
<td></td>
</tr>
<tr>
<td>begin optics</td>
<td></td>
</tr>
<tr>
<td>type snell_full</td>
<td></td>
</tr>
<tr>
<td>end optics</td>
<td></td>
</tr>
<tr>
<td>mirror_status gap_mirror_right</td>
<td></td>
</tr>
<tr>
<td>begin mirror</td>
<td></td>
</tr>
<tr>
<td>name block00_low_y_gap</td>
<td></td>
</tr>
<tr>
<td>left_medium air</td>
<td></td>
</tr>
<tr>
<td>right_medium air</td>
<td></td>
</tr>
<tr>
<td>begin optics</td>
<td></td>
</tr>
<tr>
<td>type reflec_lambertian</td>
<td></td>
</tr>
<tr>
<td>reflec 0.98</td>
<td></td>
</tr>
<tr>
<td>end optics</td>
<td></td>
</tr>
<tr>
<td>mirror_status gap_mirror_none</td>
<td></td>
</tr>
<tr>
<td>end mirror</td>
<td></td>
</tr>
<tr>
<td>end interface_low_y</td>
<td></td>
</tr>
</tbody>
</table>
begin interface_hig_y
  name block00_hig_y
  left_medium Lucite-with-dyes
  right_medium air
  begin optics
    type cholesteric
    reflec 0.04
    cholesteric_lambda 709.0
    cholesteric_delta 150
    cholesteric_width 0.0
    cholesteric_shape0 1.6
  end optics
  mirror_status gap_mirror_none
end interface_hig_y

Description of the high-Y interface (top surface)

begin interface_low_z
  name block00_low_z
  left_medium Lucite-with-dyes
  right_medium air
  begin optics
    type snell_full
  end optics
  begin mirror
    name block00_low_z_gap
    left_medium air
    right_medium air
    begin optics
      type snell_full
      reflec 0.98
    end optics
    mirror_status gap_mirror_none
  end mirror
end interface_low_z

Description of the low-Z interface (mirror foil)

begin interface_hig_z
  name block00_hig_z
  left_medium Lucite-with-dyes
  right_medium air
  begin optics
    type snell_full
  end optics
  begin mirror
    name block00_hig_z_gap
    left_medium air
    right_medium air
    begin optics
      type specular_reflection
      reflec 0.98
    end optics
    mirror_status gap_mirror_none
  end mirror
end interface_hig_z

Description of the high-Z interface (mirror foil)

end block
measurement ecn658a.eqe

Unused.
References


3. Sinke, W. and M. Zeman, The solar (r)evolution, in A tour along PV technology, economics, environment and applications, ECN.


