Implementation and Optimization of a Luminescent Down-Shifting Photovoltaic System for use in a Compound Parabolic Concentrator

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ABSTRACT: This aim of this study is to enhance the efficiency of photovoltaic (PV) cells through the inclusion of luminescent downshifting layers (LDS) to the PV cell surface. A red 'DCM' (4-(Dicyanomethylene)-2-methyl-6-(4-dimethylaminostyryl)-4H-pyran) dye has been characterized and tested for its external quantum efficiency (EQE) in varying dye concentrations before being utilized as an LDS material. Numerous different processes for spin-coating layers and soldering tabbing to the metallic strips on the solar cells were attempted, tested and optimized. The solar cells were connected in series within solar panel frames, one flat based panel system and four other compound parabolic collector frames. Their outputs were compared to quantify the effects of different frames and the inclusion of the LDS layers separately. A comparison on the enhancements made between bare, blank and LDS coated PV cells has been studied. An increase in PV cell efficiency of 4.5% has been accomplished over the 300-1100nm wavelength range when the DCM LDS layer was compared with the bare PV cell. An increase in efficiency of 6.8% has been observed in the spectral region of interest (300-500nm) with an enhancement of 10.9% in the region where silicon is least efficient (300-420nm).

KEYWORDS: External quantum efficiency, luminescent downshifting, optimization, photovoltaic.

INTRODUCTION

Luminescent Downshifting (LDS) is a method of improving the PV cells' solar responsivity through the inclusion of a layer on the cells' surface that re-emits the short wavelength light at longer wavelengths where the solar cells' have higher responsivity [1]. It converts photons of high energy (short wavelength) to photons of lower energy (hence downshifting energy) that the photovoltaic materials can more easily absorb and process. Ideally, the dye used within the layer should have a wide absorption band in the range of wavelengths that need to be enhanced and a narrow emission peak in the region where the PV cell already performs very efficiently (500-900nm). Extensive research has been completed in this area within Trinity College Dublin [2][3], and it shows that the inclusion of the LDS layer can greatly enhance PV cells' performance providing the correct dye has been selected.

Figure 1 shows the processes that occur within the LDS layer. Ideally, a dye must be selected with a high transmittance in the 500-1100 nm wavelength range (for silicon PV) in order to avoid losses due to reflection. There are inherent energy loss mechanisms which still exist and are very difficult to avoid. Some examples of these extra loss mechanisms include parasitic absorption, photon emission through the different surfaces of the layer, and even reabsorption of the downshifted photon by the LDS itself [4]. Modelling and simulation help substantially as they can provide an optimum dye concentration and LDS layer thickness which can reduce the amount of experimentation required within a laboratory tenfold [5]. The modelling process can also greatly reduce costs as less materials are used testing extensive ranges of concentrations for example.

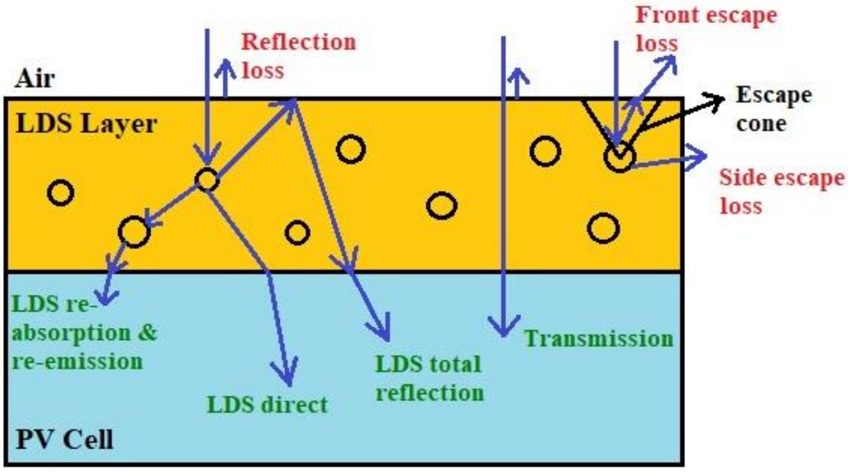


Figure 1 – LDS optical processes and loss mechanisms

The focus of this study is to build upon previous work [6] and optimize the production of LDS (figure 1) cells for application within largescale solar units such as a compound parabolic concentrator (CPC – figure 3, vs flat base figure 2) which could later be commercialized and utilized around the world to harness the solar energy. The project aims to produce uniform and reproducible layers so that the effects of the dye can be quantified. This optimization task consisted of not only improving the layer production process but also developing the method of connecting the photovoltaic (PV) cells in series. The dye used for this largescale project was called '4-(Dicyanomethylene)-2-methyl-6-(4-dimethylaminostyryl)-4*H*-pyran)' which was a red dye shortened to 'DCM'. The processes, which will be discussed in the methodology, included finding optimal dye concentrations, finding suitable layer coating methods, testing that the layer thicknesses are uniform, performing optical characteristic testing (EQE), and then deciding which connection method is best.

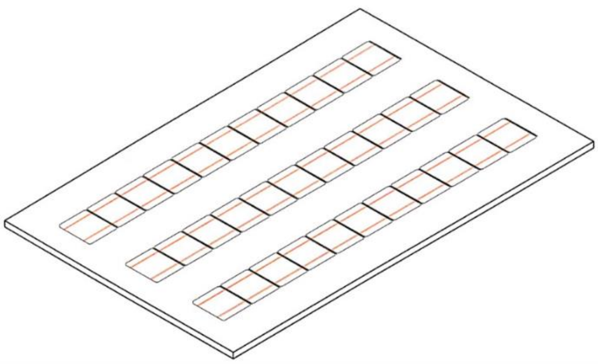


Figure 2 – Flat Base Solar Panel Frame

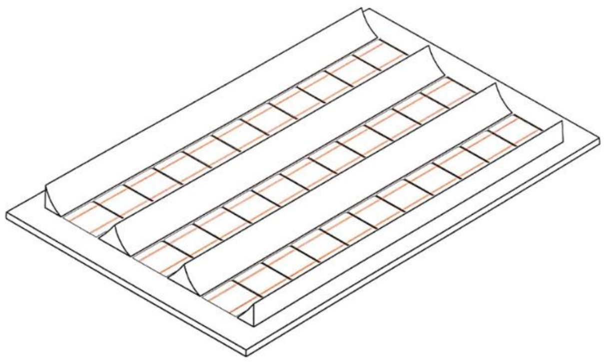


Figure 3 – CPC Base Solar Panel Frame

Comparisons are drawn between the different dye concentrations (0.1%, 0.2% & 0.3%) and their performance against the bare and blank layered PV cell will be checked. The effects of including tabbing with the two different soldering approaches will also be analyzed. An optimized final product will be decided and used within the different solar units.

1. METHODOLOGY

The methodology approach for this study is as shown in the flow chart in figure 4;

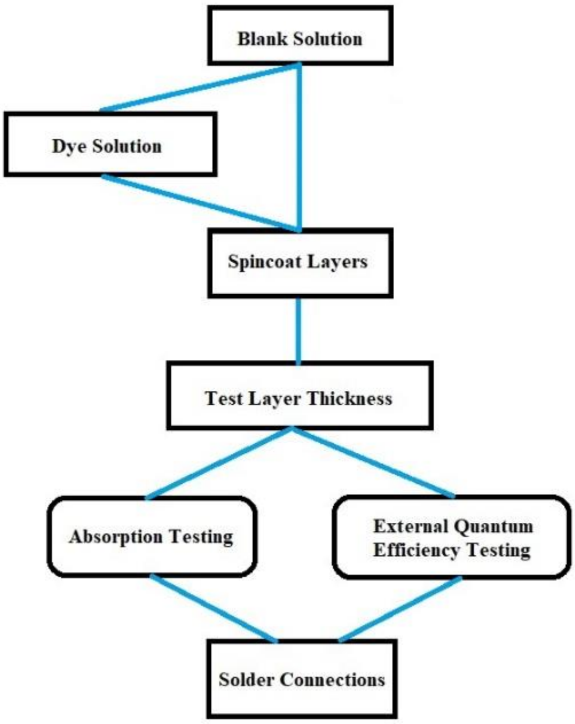


Figure 4 – Methodology Flow Chart

Blank Polymer Solution – A chloroform and PMMA mixture is produced in a 0.1% weight solution for comparison with the DCM dye layers to quantify effect of the dye on the solar power output. 11.5 grams of PMMA was added to 30ml of chloroform and mixed using a magnetic stirrer at room temperature for 30-45 minutes. Agglomeration of PMMA on the surface was found at higher percentage weights.

Dye Solution – A blank solution was prepared using the same method as above and then DCM was included at weight percentage ranges of 0.1%, 0.2% and 0.3%. This range of concentration assumption was based on previous experiments with other lumogen dyes [7] and the results, covered later, show their effectiveness.

Spin Coating – A drop casting approach was immediately discarded as it was clear that the resulting layers would be inconsistent and therefore unsuitable for a comparison study. Numerous tests were performed to determine the amount of solution to dispense on each 12.5cm^2 PV cell for spin coating. 10 ml of solution was deemed to be optimal as it had minimal wastage from solution being spun off the surface whilst also fully covering the face of the cell. This process was finalized after further trials were undertaken relating to the spin coater ramp times, chuck sizes and minimum and maximum revolutions per minute. The final recipe settled upon is an immediate 0 to 170 rpm for 170 seconds, followed by a reduction to 500rpm for 5 seconds and then finally 300rpm for another 5 seconds before coming to a stop.

LDS Layer Thickness – For a comparison study there needs to be as little difference between test subjects as possible, and since the solutions poured are exactly the same, the final test to ensure that it is a fair comparison is to check that each layer thickness is the same. This was performed using a digital micrometer at multiple locations across the layer.

Absorption Testing – Absorption testing was performed on the solution using a UV/Vis spectrometer. The solution was poured into a cuvette and placed within the device for testing in the 250-650nm wavelength range (the area of interest). A blank solution of just chloroform was used as a reference so that the resulting graphs produced are a reflection of only the dyes' absorbance and are not influenced by the solvent.

External Quantum Efficiency – Spectral response testing was performed to measure the PV cells' carriers to photon ratio. The tests were implemented on smaller 2 cm^2 PV cells which if the results were promising, would lead to upscaling to larger sizes for real world application. The cells were placed within the device directly below a monochromatic light source and connected at both positive and negative terminals. The system was calibrated before testing using a silicon reference cell supplied by the device manufacturers and the wavelength spectrum of the test was input by the user (300-1100nm in this case).

Soldering – Two different connection approaches were trialed in this study; the first being to cover the metallic strips with tape before the layer was applied so that the small area could be peeled off to ensure an adequate connection. The second approach was to produce the layers on the cell as normal and then afterwards solder the connection through the polymer surface. The results of these methods will be discussed below.

2. RESULTS AND DISCUSSION

Figure 5 below shows the progression and improvements made in layer quality after trialing different solution volumes, spin coater recipes, and pouring methods.

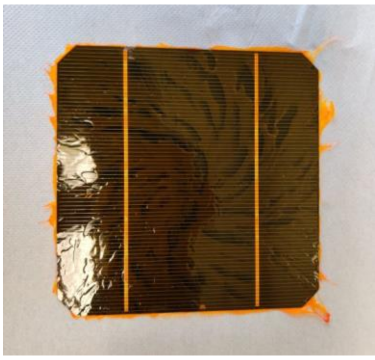


Figure 5(a)

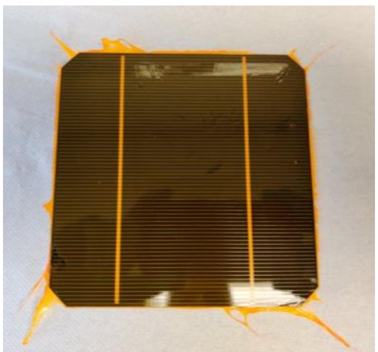


Figure 5 (b)

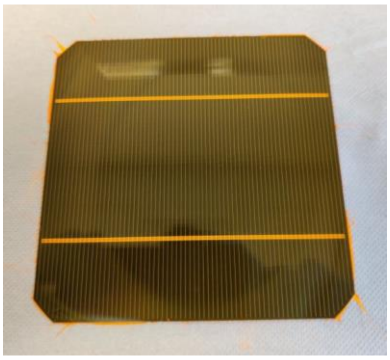


Figure 5 (c)

Figure 5(a) demonstrates the layer quality with no variables decided (i.e. no set solution amount or spin coater recipe selected) and it is clear that it was unsuitable for use within a solar unit. Figure 5(b) shows some progression made as the decision to use 10ml of solution was finalized, this was poured using a syringe so that a fair 10ml was distributed each time. The final product is displayed in figure 5(c), which is the end result of finding a suitable solution volume and spincoater recipe, it is clear that the final layer is of much higher quality than initial attempts.

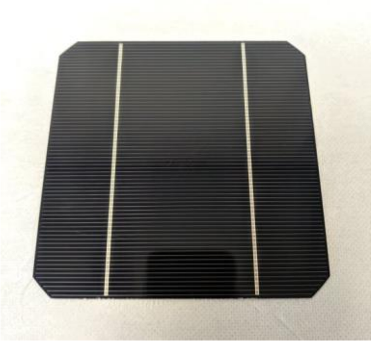


Figure 6 – Blank layer quality to be compared with dye layer in figure 6 above

Figure 6 above shows the quality of layer using blank solution (i.e. without DCM) using the same recipe as before. It is clear that there are minimal defects observable. Each layer produced was checked at multiple locations on their surface for their thicknesses using a digital micrometer, and it was found that all of the layers produced were uniformly 20 microns thick.

Figure 7 below demonstrates why placing tape over the connection strips and peeling them off after a layer had been poured on top did not work. No matter how carefully the layer was sliced into with a scalpel and tape peeled back, the cell would either crack or there would be extensive damage to the face of the layer.

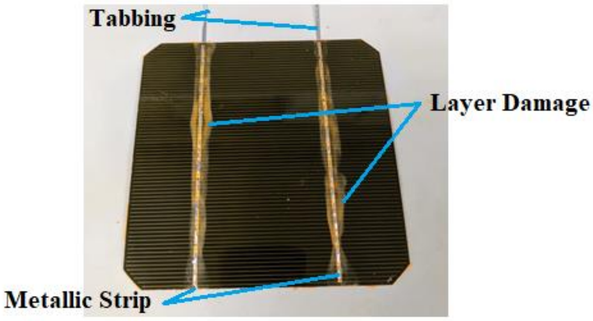
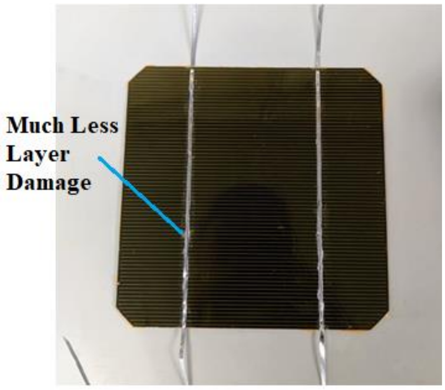
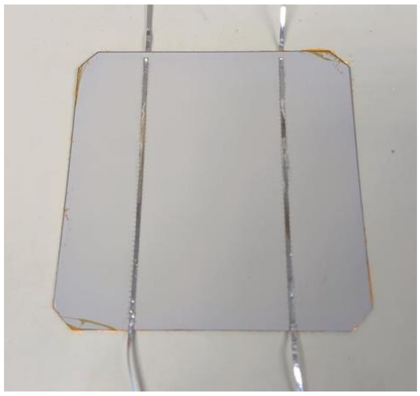


Figure 7 – PV cell after attempting to solder tabbing after peeling off protective tape

After discarding the tape peeling attempts, an approach of soldering directly through the LDS layer was tested instead. Figures 8 and 9 below clearly indicate how this process produced much higher quality layers and connections.





Figures 8, 9 – PV connections made after soldering through the LDS layer

Finally, in relation to cell connectivity, figure 10 below shows how the PV cells were connected in series.

Figure 10 – Series connection through tabbing soldering

The metallic strips observed in the figures above are tabbing that was included to increase the amount of current that the PV cells would be able to transfer along in series. The effects of the tabbing on the external quantum efficiency measurements will be shown below in graphic form. Each PV cell was connected from top surface (positive) to bottom surface (negative) in an alternating fashion.

Included on the following page in figures 11 & 12 are the resulting graphs from EQE tests performed on the multiple different cells.

Figure 11 demonstrates why the 0.1% weight DCM solution was selected for the largescale project. Whilst all 3 concentrations tested performed similarly from approximately 450 to 1100nm, the 0.1% solution performed substantially better in the 300-420nm range which is where silicon displays its lowest efficiency levels. A bare cell (black line) is included for comparison. The increase in external quantum efficiency for the spectrum of 300-1100nm tested was 4.5%.

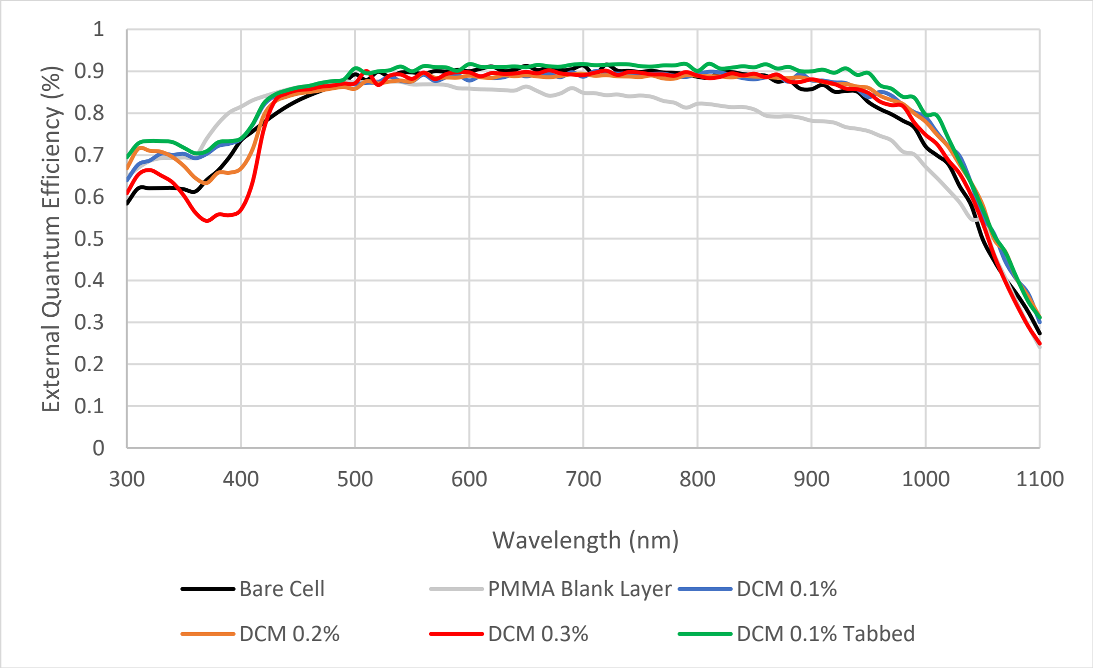


Figure 11 – EQE of DCM in varying weight percentages with and without tabbing

Figure 11 also shows the effect that the inclusion of soldered tabbing had on the cells' efficiency. DCM at 0.1% concentration with tabbing is the best performing PV cell setup tested in the group so far. Figure 12 below shows more clearly why tabbing was introduced to the cells as it improved the connectivity of the PV cells in series. You can see that the 300-380nm region in particular was enhanced.

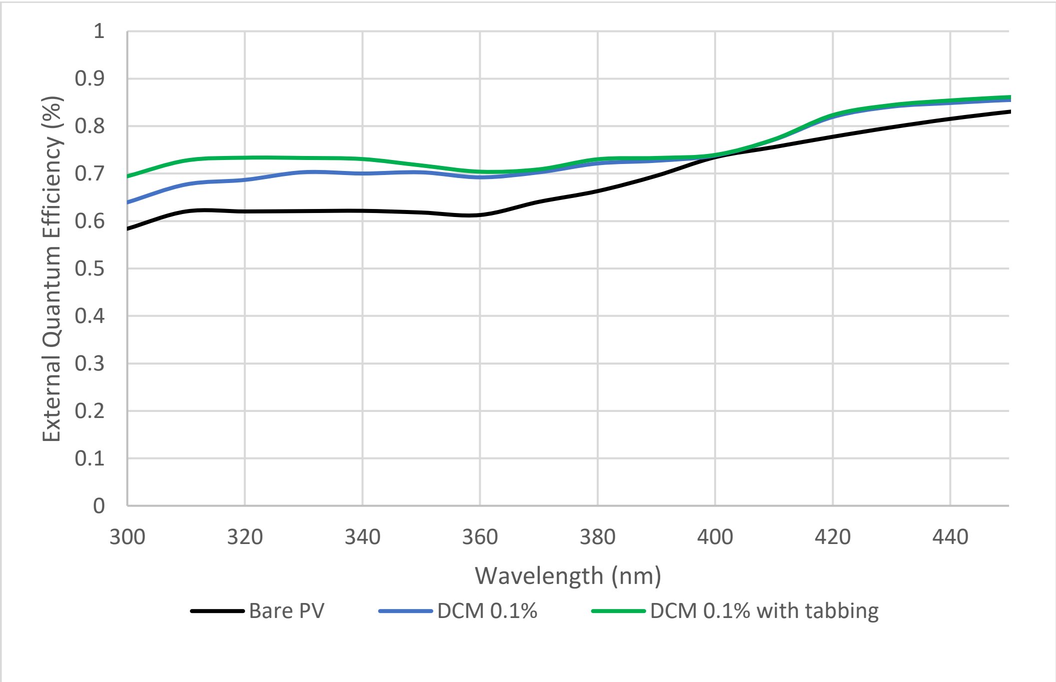


Figure 12 – EQE of 0.1% DCM with tabbing vs bare PV cell

The 0.1% DCM tabbing results gives an increase in efficiency of 6.8% over the spectral region of interest (300-500nm) with an enhancement of 10.9% in the wavelength region where silicon PV is least efficient (300-420nm).

CONCLUSION

To conclude, it is evident that the inclusion of the DCM dye within the LDS layers was a success as it has enhanced the PV cells' efficiency substantially. 0.1% DCM with tabbing is the best performing LDS application thus far within the group. Efficiency improvements of 4.5% overall have been calculated across the entire 300-100nm spectrum, with local enhancements of 6.8% (300-500nm) and 10.9% (300-420nm) in the regions where the silicon PV cells are known to perform poorly relatively. The DCM results are very promising for application within solar panel commercialization for households. The layer production methods have been optimized as uniformly reproducible layers have been created, and the benefits of the inclusion of tabbing to the connections have been shown.

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