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Research on Luminescent Solar Concentrators (LSCs)

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ABSTRACT

Research on Luminescent Solar Concentrators (LSCs) is crucial for enhancing the energy density of sunlight and lowering the costs associated with silicon solar cells. This paper thoroughly evaluates and compares the performance of three different LSC materials: Rhodamine B (RBB), Rhodamine 6G (R6G), and Coumarin 6 (C6). The study focuses on several key metrics, including Stokes shift, external quantum efficiency, concentration factor, and conversion factor. By analyzing these parameters, the paper aims to elucidate how each material's properties influence overall performance, providing valuable insights into optimizing LSC design for improved energy harvesting. In order to pave the way for more widespread adoption of LSCs in solar applications, enhancing their role in sustainable energy systems.

KEYWORDS

Concentrating Radiation; Photocurrent; Conversion Efficiency; Electrical Properties; Output Performance.

1. INTRODUCTION

1.1. Background

A luminescent solar concentrator (LSC) is a device for concentrating radiation, solar radiation in particular, to produce electricity. Luminescent solar concentrators operate on the principle of collecting radiation over a large area, converting it by luminescence (specifically by fluorescence) and directing the generated radiation into a relatively small output target.

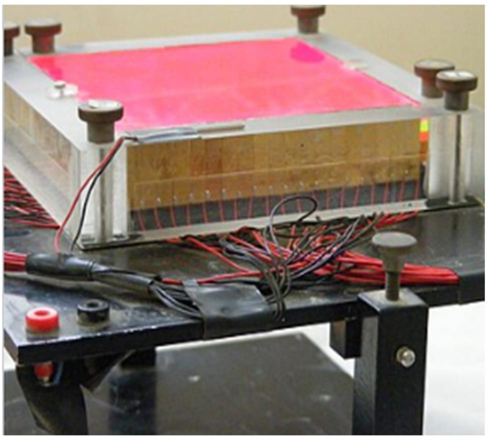


Figure 1. A luminescent solar concentrator

Initial designs typically comprised parallel thin, flat layers of alternating luminescent and transparent materials, placed to gather incoming radiation on their (broader) faces and emit concentrated radiation around their (narrower) edges.[1][2] Commonly the device would direct the concentrated radiation onto solar cells to generate electric power.

Other configurations (such as doped or coated optical fibers, or contoured stacks of alternating layers) may better fit particular applications.

The layers in the stack may be separate parallel plates or alternating strata in a solid structure. In principle, if the effective input area is sufficiently large relative to the effective output area, the output would be of correspondingly higher irradiance than the input, as measured in watts per square metre. The concentration factor is the ratio between output and input irradiance of the whole device.

For example, imagine a square glass sheet (or stack) 200 mm on a side, 5 mm thick. Its input area (e.g. the surface of one single face of the sheet oriented toward the energy source) is 10 times greater than the output area (e.g. the surface of four open sides) - 40000 square mm (200x200) as compared to 4000 square mm (200x5x4). To a first approximation, the concentration factor of such an LSC is proportional to the area of the input surfaces divided by the area of the edges multiplied by the efficiency of diversion of incoming light towards the output area. Suppose that the glass sheet could divert incoming light from the face towards the edges with an efficiency of 50%. The hypothetical sheet of glass in our example would give an output irradiance of light 5 times greater than that of the incident light, producing a concentration factor of 5.

Similarly, a graded refractive index optic fibre 1 square mm in cross section, and 1 metre long, with a luminescent coating might prove useful.

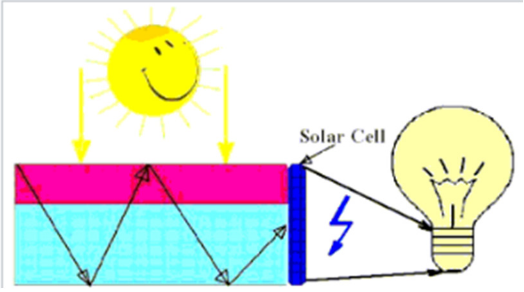


Figure 2. LSC scheme diagram

The concentration factor interacts with the efficiency of the device to determine overall output.

The concentration factor is the ratio between the incoming and emitted irradiance. If the input irradiance is 1 kW/m^2 and the output irradiance is 10 kW/m^2, that would provide a concentration factor of 10.

The efficiency is the ratio between the incoming radiant flux (measured in watts) and the outgoing wattage, or the fraction of the incoming energy that the device can deliver as usable output energy (not the same as light or electricity, some of which might not be usable). In the previous example, half the received wattage is re-emitted, implying efficiency of 50%.

Most devices (such as solar cells) for converting the incoming energy to useful output are relatively small and costly, and they work best at converting directional light at high intensities and a narrow frequency range, whereas input radiation tends to be at diffuse frequencies, of relatively low irradiance and saturation. Concentration of the input energy accordingly is one option for efficiency and economy.

1.2. Stokes Shift

Stokes shift is the difference (in energy, wavenumber or frequency units) between positions of the band maxima of the absorption and emission spectra (fluorescence and Raman being two examples) of the same electronic transition. It is named after Irish physicist George Gabriel Stokes. Sometimes Stokes shifts are given in wavelength units, but this is less meaningful than energy, wavenumber or frequency units because it depends on the absorption wavelength. For instance, a 50 nm Stokes shift from absorption at 300 nm is larger in terms of energy than a 50 nm Stokes shift from absorption at 600 nm.

When a system (be it a molecule or atom) absorbs a photon, it gains energy and enters an excited state. One way for the system to relax is to emit a photon, thus losing its energy (another method would be the loss of energy as translational mode energy via vibrational-translational or electronic-translational collisional processes with other atoms or molecules). When the emitted photon has less energy than the absorbed photon, this energy difference is the Stokes shift.

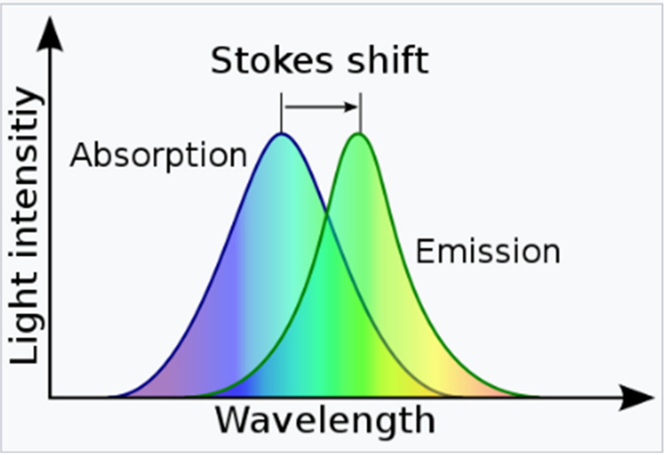


Figure 3. Stoke Shift

The Stokes shift is primarily the result of two phenomena: vibrational relaxation or dissipation and solvent reorganization. A fluorophore is a dipole, surrounded by solvent molecules. When a fluorophore enters an excited state, its dipole moment changes, but surrounding solvent molecules cannot adjust so quickly. Only after vibrational relaxation do their dipole moments realign.

Lowering the cost of generation per unit of power is one of the most important issues in global solar photovoltaic (PV) energy technology today. Fundamental research toward reaching high conversion efficiency goes hand in hand with those on lowering production costs. Concentrating sunlight is considered an important way to decrease the cost of PV electricity generation, as the rise of the energy density will reduce the usage area of PV cells dramatically. Therefore, the concept of a luminescent solar concentrator (LSC) was proposed in solar energy conversion to serve the above beneficial purposes. An important advantage of LSCs as light-collecting devices is that they are active under both direct and diffuse illumination, while traditional mirror- or lens-based concentrators operate only under direct solar illumination and thus require high-precision tracking.

1.3. Luminescent Solar Concentrators

Luminescent solar concentrators are light management devices that consist of a large-area slab of a transparent material serving as a low-loss waveguide impregnated or coated with highly luminescent fluorophores such as organic dyes, and quantum dots.

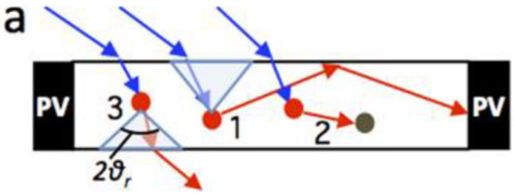


Figure 4. Schematic depiction of LSC schematic LSC edge-attached with PV cell

In Figure 4 incident light (blue arrows) with wavelength, λ1 is absorbed by fluorophores (red dots) embedded into a transparent waveguide and re-emitted at a longer wavelength λ2 (red arrows). Re-emitted photons can be either trapped by total internal reflection and waveguided to PVs at device edges (pathway 1) or lost due to non-radiative recombination following reabsorption (pathway 2) or "leakage" through the escape cone with the size defined by the angle of total internal reflection θ_r (pathway 3).

As illustrated in Figure 5, light impinging onto a large-area front side of the slab (incident photon flux Φ_1) is absorbed by the fluorophores and re-emitted at a longer wavelength. Even without special reflecting coatings, a significant fraction of emitted radiation is trapped by total internal reflection and wave-guided toward the edges of the slab where it can be collected (flux $\varnothing_2''\Phi_2$) by PV cells. Due to a potentially large difference between the area of the front surface of the slab exposed to solar light (A_1) and the area of its edges (A_2), this device serves as a solar concentrator, that is, it can increase the flux density incident onto the PV ($\phi_2 = \varnothing_2''/A_2$) compared to the original flux density ($\phi_1 = \Phi_1/A_1$);

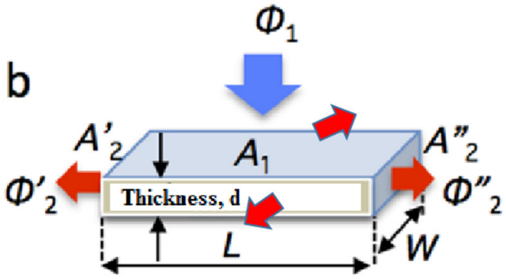


Figure 5. Fraction of incident flux impinging onto a front surface is absorbed by LSC fluorophores, reemitted and guided toward edges of the device

In quantitative terms, the LSC concentration factor, $C = \varphi_2 / \varphi_1$ can be thought as an effective enlargement (or contraction) factor of an area of a PV device. When C is greater than 1, the use of an LSC leads to increased photocurrent if compared to the situation where the PV is directly exposed to sunlight. Concentration factor can be rewritten as $C = G\eta_{opt}$. ***G*** is geometric gain factor is defined by the ratio of A_1 and $A_2 = A_2' + A_2''$, as in Equation (1)

$$G = \frac{surface\ area\ of\ the\ top\ face, A_1}{surface\ area\ of\ the\ edges, A_2} \tag{1}$$

and η_{opt} is external quantum yield of the device which can be expressed as in Equation (2).

$$\eta_{opt} = \frac{\Phi_1}{\Phi_2} \tag{2}$$

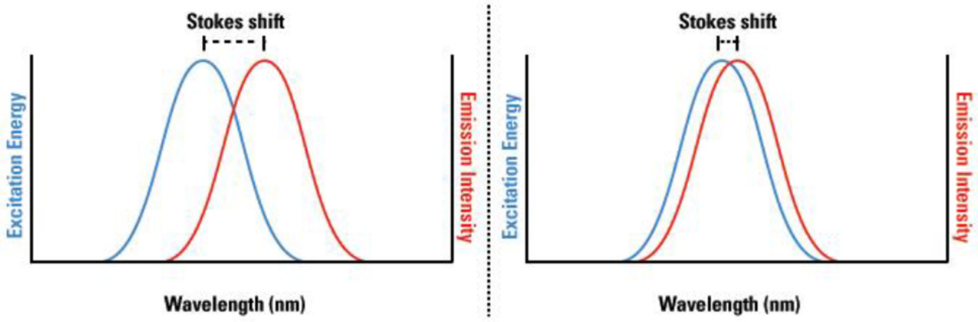


Figure 6. Comparison of Stokes shift before (left) and after (right) proper LSC design improvement

A desired result of the LSC device is possessing weak self-absorption. Stock's shift can be defined as the distance between the excitation and emission wavelengths. Using an appropriately design of LSC, one can considerably reduce losses due to reabsorption of the waveguided radiation.

1.4. Explanation of Related Parameters

Here we attempt to develop a simple analytical approach for an express evaluation of prospective performance of LSCs by plotting a photocurrent density-voltage (J–V) curve. J–V curve is determined by measuring current and voltage of a silicon photovoltaic (PV) solar cell attached to one edge of a LSC plate in order to characterization the optical conversion and concentration efficiency of fabricated LSC. Some important parameters in J–V curves, including:

1.4.1. Short Circuit Current Density (J_{SC})

The short circuit current density J_{SC} is determined when the voltage equals 0. When comparing the performance of two solar devices, it is common to normalize the current by dividing by the illuminated cell area. In this way, the current density values are compared. Current density is expressed as mA cm^{-2}.

1.4.2. Open Circuit Voltage (V_{OC})

The open circuit voltage (V_{OC}) occurs when there is no current passing through the cell.

1.4.3. Maximum Power P_T or P_{MAX}

The power produced by the cell in Watts can be easily calculated along the J-V sweep by the equation P=JV. At the theoretical maximum value for power occurs between the J_{SC} and V_{OC} points, so called as P_T. The measured voltage multiply current to obtain maximum power point, P_{MAX} are denoted as V_{MP} and J_{MP} respectively.

1.4.4. Filling Factor (FF)

Filling factor (FF) can also be interpreted graphically as the ratio of the rectangular areas depicted in Figure 7. Getting an FF value from J-V sweep is comparing the maximum power, P_{MAX} to the theoretical power (P_T), as shown in Equation (3).

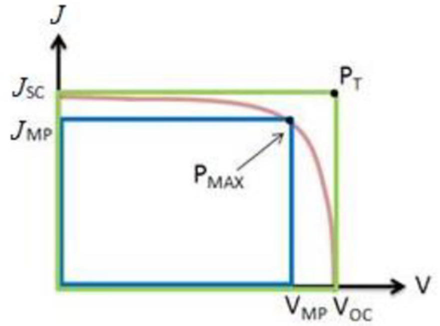


Figure 7. Schematic representation of current-voltage characteristics of a solar cell

$$FF = \frac{P_{MAX}}{P_T} = \frac{J_{MP} \times V_{MP}}{J_{SC} \times V_{OC}} \quad (3)$$

Solar cells are measured under the incident light is described by the AM1.5 spectrum and has an irradiance of Iin= 100 mW/cm^2. The conversion efficiency, $\eta conversion$ is calculated as the ratio between the maximal generated power and the incident power, the following Equation (4) has been applied.

$$\eta_{conversion} = \frac{J_{SC} \times V_{OC} \times FF}{Total\ power\ intentisity\ of\ light, I_{in}} \qquad (4)$$

2. MAIN EQUIPMENT

a. Fluorescence Spectrophotometer

b. Solar simulator

c. Source Measure Unit

d. Vacuum oven

e. Solar cell

3. PROCEDURE

3.1. Procedures to Prepare LSC

a. A plastic container was provided, and 2ml of epoxy solution was taken into it.

b. The epoxy solution was mixed with 1ml of organic dye stock solution.

c. The plastic container was covered with aluminum foil, and a few holes were punched on top.

d. The container was placed into a vacuum oven under vacuum conditions, and the temperature was set to 50 degrees Celsius.

e. After 15 minutes, the plastic container was taken out from the vacuum oven.

f. 1ml of hardener was added into the container, and it was mixed well.

g. The mixture was poured into a silicone mold and allowed to dry for 24 hours.

3.2. Procedures to Justify the Performance of LSC

3.2.1. To Determine Stoke's Shift of the Fabricated LSC

a. The 3-D peak measurement was carried out utilizing a fluorescence spectrophotometer coupled to an integrating sphere to justify the excitation, E_x, and emission, E_m, spectra range.

b. The determination of the Stoke shift was made by comparing the excitation peak and emission spectra.

3.2.2. To Evaluate Luminescence Performance of the Fabricated LSC

a. The emission E_m spectrum curve was obtained by applying the E_x value in the "Spectrum manager" interface.

b. The external quantum efficiency, EQY, of the sample was determined using a fluorescence spectrophotometer, and the record of the template name is documented in Table 1.

c. The EQY obtained from step (2) was designated as "total optical efficiency from all surfaces."

d. Black carbon paint was applied to cover the edges of a similar LSC, restricting light emission solely from the top and bottom faces of the device.

e. The procedures from (1) to (2) were repeated, and the results were consolidated into Table 1.

f. The curve resulting from this process was named "total optical efficiency from the top and bottom surfaces."

g. From Table 1, the "total optical efficiency from the edges" was determined.

3.2.3. To Determine the Concentrating Factor, C

a. The dimensions of the LSC were measured.

b. The geometric gain, G, for the fabricated LSC was calculated using Equation (1).

c. The concentration factor, $C = G\eta_{opt}$, where G is the geometric gain and ηopt is the external quantum yield, was computed.

3.2.4. To Determine the Energy Conversion

a. The fabricated LSC was assembled with a commercial silicon PV cell, as depicted in Figure 1.

b. A solar simulator was applied, featuring air mass 1.5 global illumination (AM 1.5G, 100mW/cm2), along with a source meter for current versus voltage, I-V characterization.

c. The results were recorded and exported.

d. The current density, J, of the results was determined.

e. A graph was plotted to compare the J-V characteristic of the dark condition, with and without the fabricated LSC device.

f. From the graph plotted in (5), the short-circuit current density, J_{SC}, and open-circuit voltage, V_{OC}, were determined.

g. The filling factor, FF, and energy conversion efficiency, $\eta_{conversion}$, were calculated.

h. The results from (4) and (7) were summarized into Table 2.

4. RESULT ANALYSIS

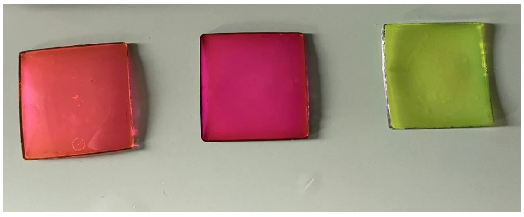


Figure 8. Prepared LSC samples, from left to right: R6G, RBB and C6

4.1. To Determine Stokes Shift of the Fabricated LSC

$$\Delta\lambda = \Delta\lambda_{Em} - \Delta\lambda_{Ex}$$

4.1.1. RBB (Red)

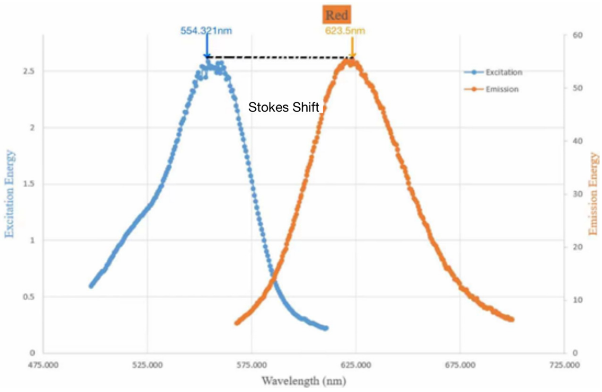


Figure 9. Stokes shift of RBB sample

$$\Delta\lambda = \Delta\lambda_{Em} - \Delta\lambda_{Ex} = 623.5nm - 554.321nm = 78.179nm$$

4.1.2. R6G (Orange)

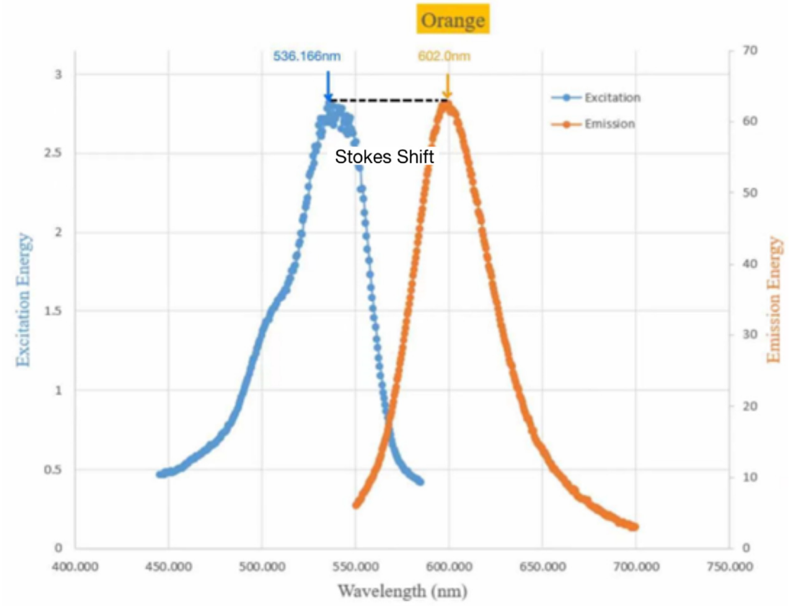


Figure 10. Stokes shift of R6G sample

$$\Delta\lambda = \Delta\lambda_{Em} - \Delta\lambda_{Ex} = 602.0nm - 536.166nm = 65.834nm$$

4.1.3. C6 (Green)

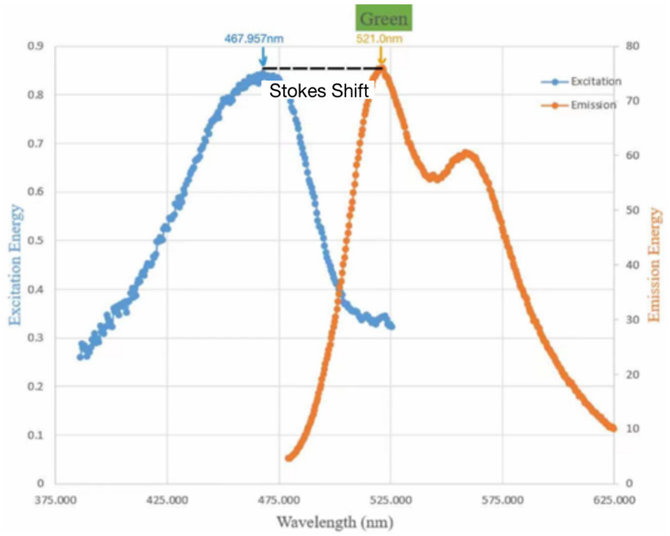


Figure 11. Stokes shift of C6 sample

$$\Delta\lambda = \Delta\lambda_{Em} - \Delta\lambda_{Ex} = 521.0nm - 467.957nm = 53.043nm$$

4.1.4. Comparation

Table 1. Comparation (1)

	RBB (Red)	R6G (Orange)	C6 (Green)
$\Delta\lambda$ (nm)	78.179	65.834	53.043

4.2. To Evaluate Luminescence Performance of the Fabricated LSC

$$\begin{aligned} &Ext.quantum\ yield\ of\ Sides\ (\%) \\ &\qquad = Ext.quantum\ yield\ of\ All\ (\%) \\ &\qquad - Ext.quantum\ yield\ of\ Top\ and\ Bottom\ (\%) \end{aligned}$$

4.2.1. RBB (Red)

$$\begin{aligned} &Ext.quantum\ yield\ of\ Sides\ (\%) \\ &\qquad = Ext.quantum\ yield\ of\ All\ (\%) \\ &\qquad - Ext.quantum\ yield\ of\ Top\ and\ Bottom\ (\%) = 30.181\% - 10.452\% \\ &\qquad = 19.729\% \end{aligned}$$

4.2.2. R6G (Orange)

$$\begin{aligned} &Ext.quantum\ yield\ of\ Sides\ (\%) \\ &\qquad = Ext.quantum\ yield\ of\ All\ (\%) \\ &\qquad - Ext.quantum\ yield\ of\ Top\ and\ Bottom\ (\%) = 32.003\% - 22.600\% \\ &\qquad = 9.403\% \end{aligned}$$

4.2.3. C6 (Green)

$$\begin{aligned} &Ext.quantum\ yield\ of\ Sides\ (\%) \\ &\qquad = Ext.quantum\ yield\ of\ All\ (\%) \\ &\qquad - Ext.quantum\ yield\ of\ Top\ and\ Bottom\ (\%) = 53.364\% - 12.781\% \\ &\qquad = 40.583\% \end{aligned}$$

4.2.4. Comparation

Table 2. Comparation (2)

	Ext. quantum yield of All (%)	Ext. quantum yield of Top and Bottom (%)	Ext. quantum yield of Sides (%)
RBB (Red)	30.181	10.452	19.729
R6G (Orange)	32.003	22.600	9.403
C6 (Green)	53.364	12.781	40.583

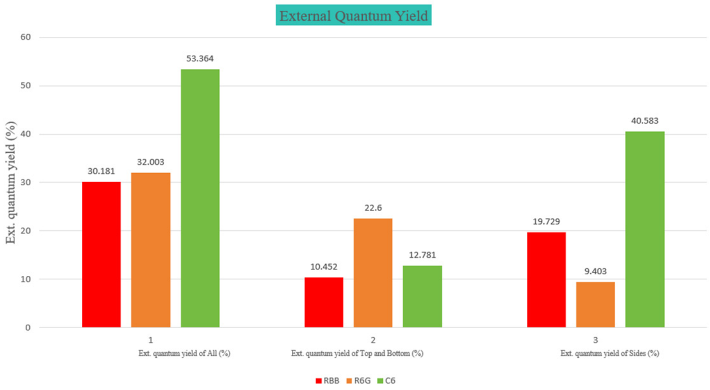


Figure 12. External quantum yield of different LSC samples

4.3. To Determine the Concentrating Factor, C

$$C = M \times \eta_{opt}, where\ M = \frac{Top\ Area}{Sides\ Area}$$

$$and\ \eta_{opt} = \text{Ext. quantum yield of Sides (\%)}$$

4.3.1. RBB (Red)

The top is square

$$Length\ of\ RBB = \frac{1}{3} \times (49.92mm + 49.52mm + 49.62mm) = 49.687mm$$

$$Thickness\ of\ RBB = \frac{1}{4} \times (0.765mm + 0.710mm + 0.585mm + 0.585mm) = 0.661mm$$

$$C = M \times \eta_{opt} = \frac{(49.687mm)^2}{4 \times 49.687mm \times 0.661mm} \times 19.729\% = 4.011$$

4.3.2. R6G (Orange)

The top is square

$$Length\ of\ R6G = \frac{1}{4} \times (49.52mm + 49.72mm + 49.72mm + 49.60mm) = 49.640mm$$

$$Thickness\ of\ R6G = \frac{1}{3} \times (0.675mm + 0.775mm + 0.705mm) = 0.718mm$$

$$C = M \times \eta_{opt} = \frac{(49.640mm)^2}{4 \times 49.640mm \times 0.718mm} \times 9.403\% = 1.625$$

4.3.3. C6 (Green)

The top is square

$$Length\ of\ C6 = \frac{1}{4} \times (49.80mm + 49.50mm + 49.84mm + 49.52mm) = 49.665mm$$

$$Thickness\ of\ C6 = \frac{1}{4} \times (0.655mm + 0.723mm + 0.595mm + 0.625mm) = 0.675mm$$

$$C = M \times \eta_{opt} = \frac{(49.665mm)^2}{4 \times 49.665mm \times 0.675mm} \times 19.729\% = 3.628$$

4.3.4. Comparation

Table 3. Comparation (3)

	RBB (Red)	R6G (Orange)	C6 (Green)
Concentrating factor, C	4.011	1.625	3.628

4.4. To Determine the Energy Conversion

How to determine some values:

I_{sc}: The current when voltage=0.

V_{oc}: The voltage when current=0.

V_{max}: Through the Pover density vs Voltage curve, the corresponding V value when P is the maximum is V_{max}.

I_{max}: Through the Current vs Voltage curve, the corresponding I value when V is the maximum is I_{max}.

$$J_{SC} = \frac{I_{sc}}{A}$$

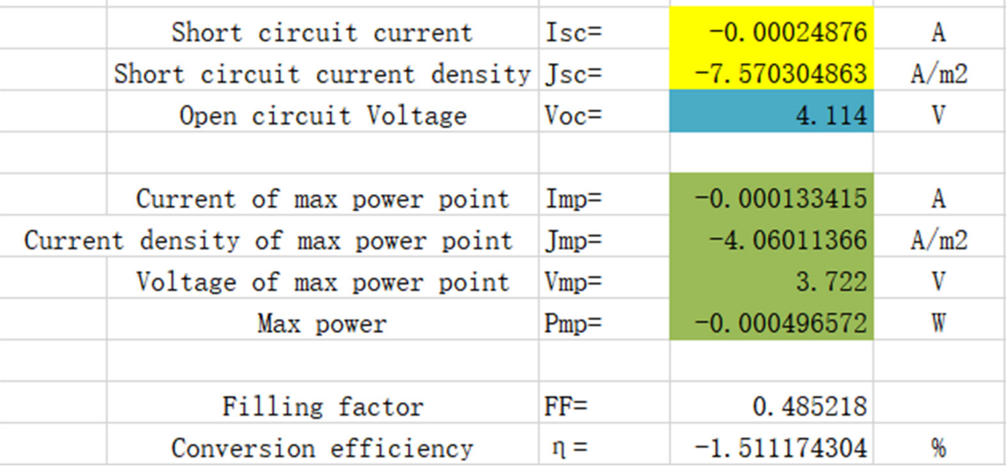
$$J_{max} = \frac{I_{max}}{A}$$

$$FF = \frac{P_{ideal}}{P_{max}} = \frac{I_{sc}V_{oc}}{I_{max}V_{max}}$$

$$\eta_{conversion} = \frac{J_{sc}V_{oc}FF}{Total\ power\ intentisity\ of\ light, I_{in}}$$

4.4.1. RBB (Red)

4.4.1.1 Result



	Short circuit current	Isc=	-0.00024876	A
	Short circuit current density	Jsc=	-7.570304863	A/m2
	Open circuit Voltage	Voc=	4.114	V
	Current of max power point	Imp=	-0.000133415	A
	Current density of max power point	Jmp=	-4.06011366	A/m2
	Voltage of max power point	Vmp=	3.722	V
	Max power	Pmp=	-0.000496572	W
	Filling factor	FF=	0.485218	
	Conversion efficiency	η=	-1.511174304	%

Figure 13. Energy conversion efficiency of RBB sample

4.4.1.2 Power Density vs Voltage

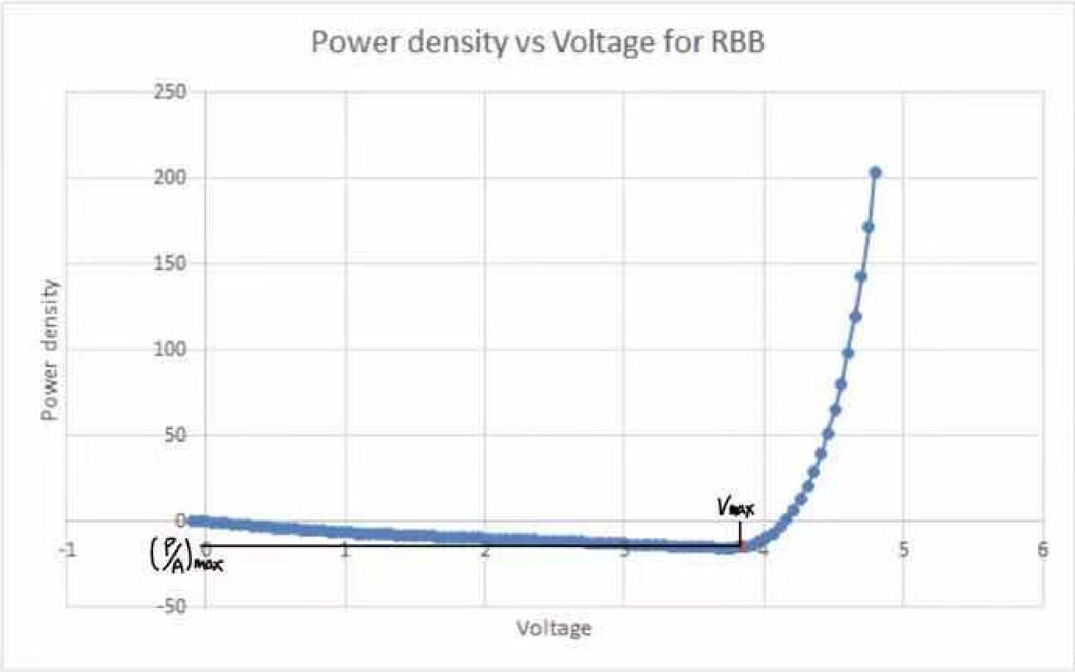


Figure 14. PV curve of RBB sample

4.4.1.3 IV Curve

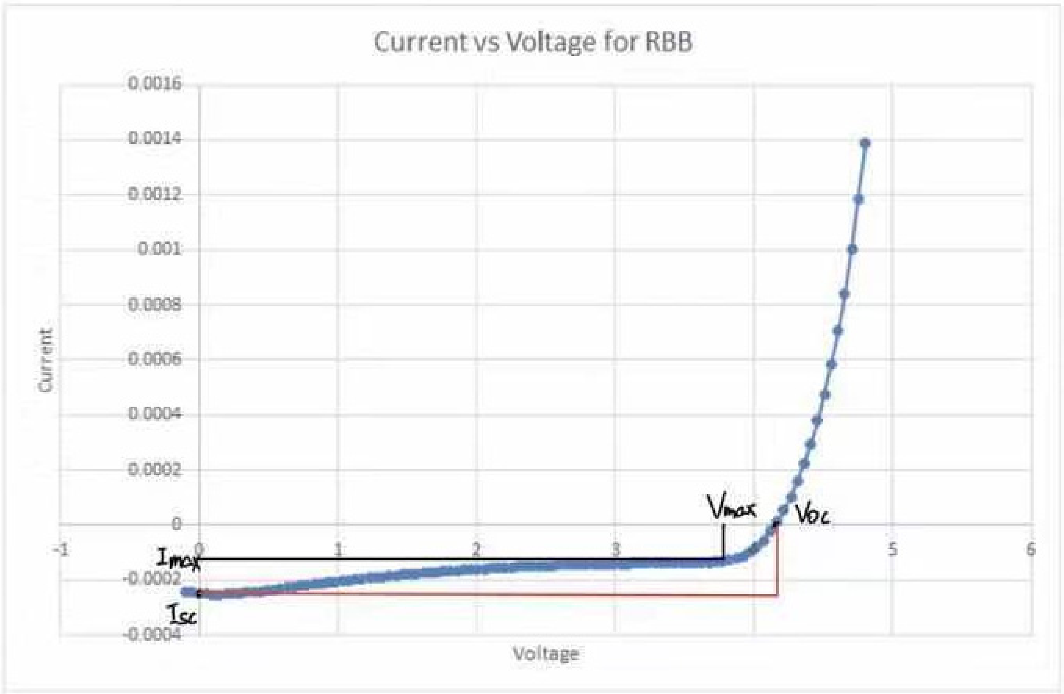


Figure 15. IV curve of RBB sample

4.4.1.4 JV Curve

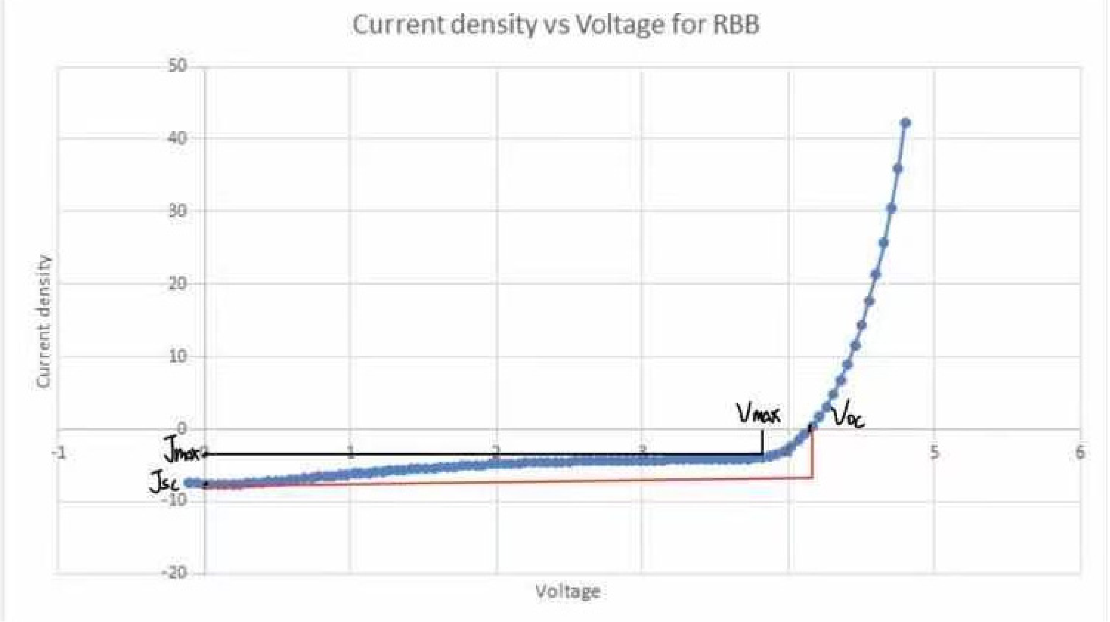


Figure 16. JV curve of RBB sample

4.4.1.5 Comparation between Dark, with and Without LSC

Comparing the I-V diagram and J-V diagram of LSC, Dark and Light reference, it can be found that the area enclosed by I_{sc} (J_{sc}) and V_{oc} of the Dark group is particularly small, while the area enclosed by I_{sc} (J_{sc}) and V_{oc} of the Light reference is larger than that of the Dark group. The group is larger, but smaller than the LSC group (only the third quadrant is considered). This proves the light-gathering effect of LSC. For RBB, the curve of the Light reference group is very close to that of the RBB group, which may be due to design defects (uneven or bent surface).

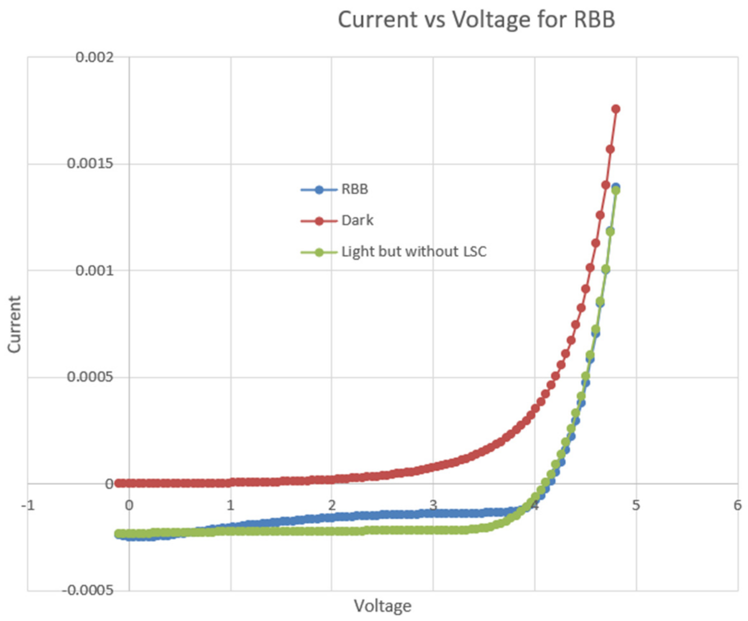


Figure 17. Comparison between dark, with and without LSC IV curves (RBB)

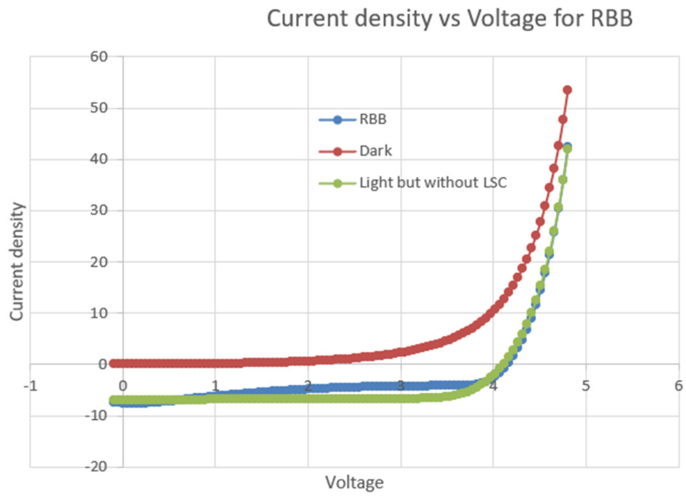
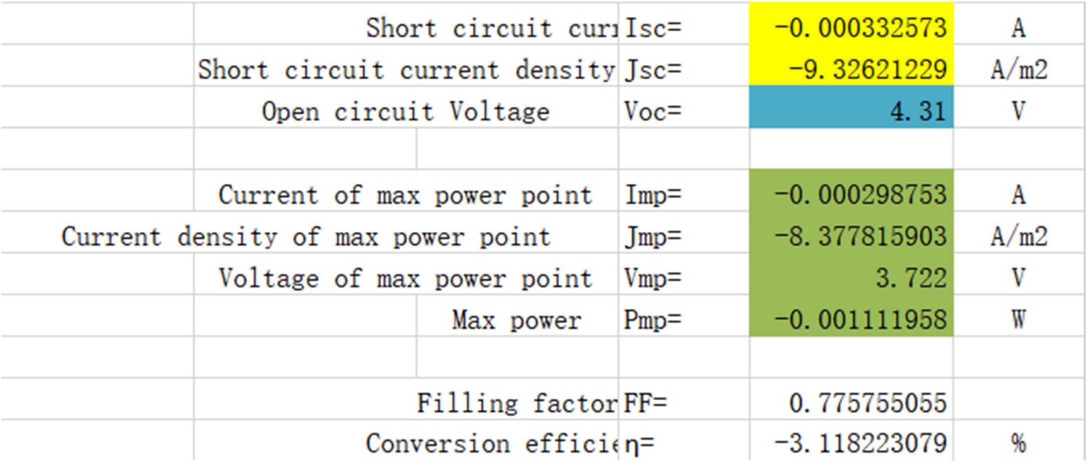


Figure 18. Comparison between dark, with and without LSC JV curves (RBB)

4.4.2. R6G (Orange)

4.4.2.1 Result



	Short circuit cur	Isc=	-0.000332573	A
	Short circuit current density	Jsc=	-9.32621229	A/m2
	Open circuit Voltage	Voc=	4.31	V
	Current of max power point	Imp=	-0.000298753	A
	Current density of max power point	Jmp=	-8.377815903	A/m2
	Voltage of max power point	Vmp=	3.722	V
	Max power	Pmp=	-0.001111958	W
	Filling factor	FF=	0.775755055	
	Conversion efficie	η=	-3.118223079	%

Figure 19. Energy conversion efficiency of R6G sample

4.4.2.2 Power Density vs Voltage

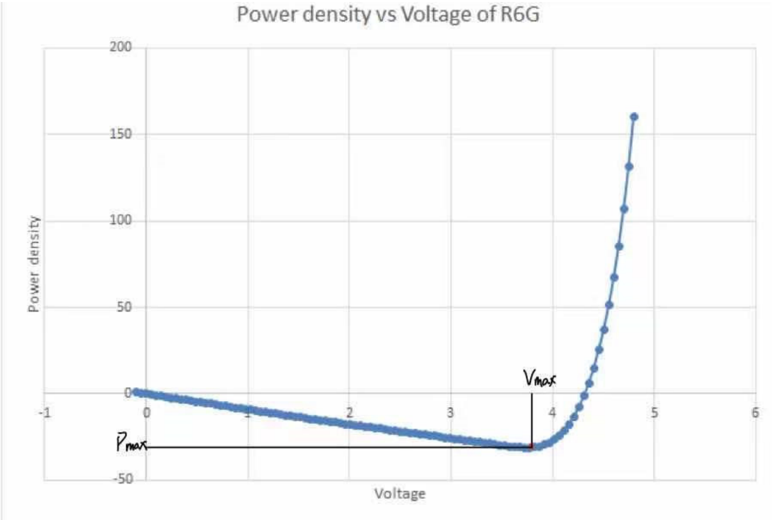


Figure 20. PV curve of R6G sample

4.4.2.3 IV Curve

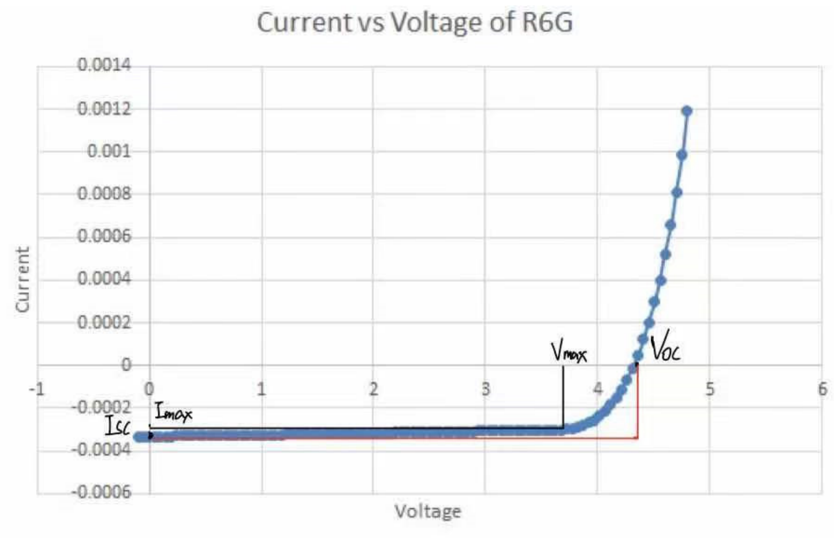


Figure 21. IV curve of R6G sample

4.4.2.4 JV Curve

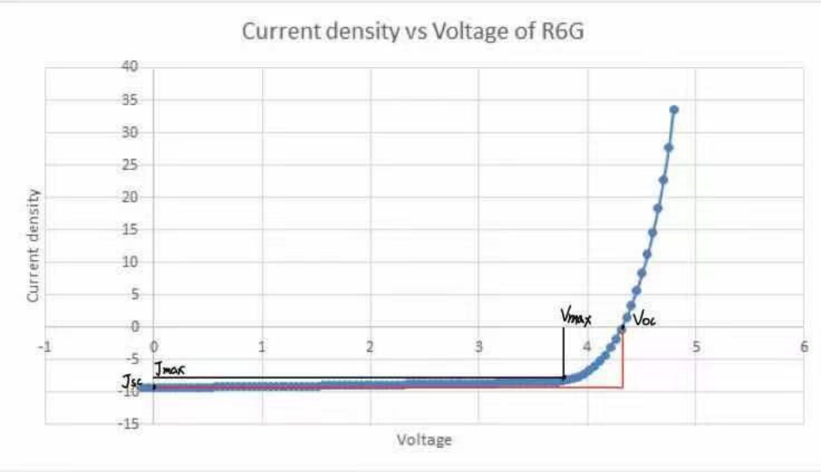


Figure 22. JV curve of R6G sample

4.4.2.5 Comparation between Dark, with and Without LSC

Comparing the I-V diagram and J-V diagram of LSC, Dark and Light reference, it can be found that the area enclosed by I_{sc} (J_{sc}) and V_{oc} of the Dark group is particularly small, while the area enclosed by I_{sc} (J_{sc}) and V_{oc} of the Light reference is larger than that of the Dark group. The group is larger, but smaller than the LSC group (only the third quadrant is considered). This proves the light-gathering effect of LSC.

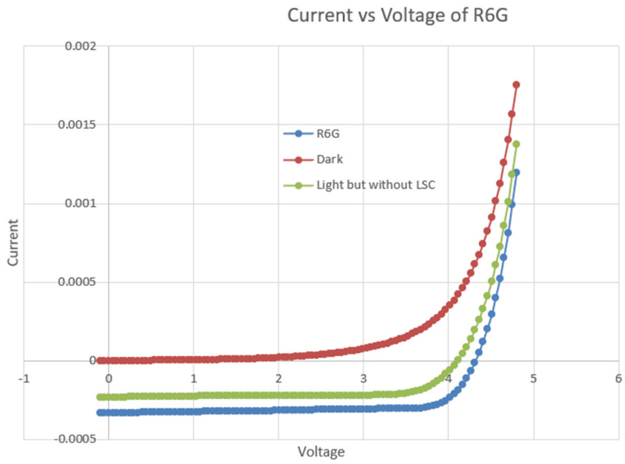


Figure 23. Comparison between dark, with and without LSC IV curves (R6G)

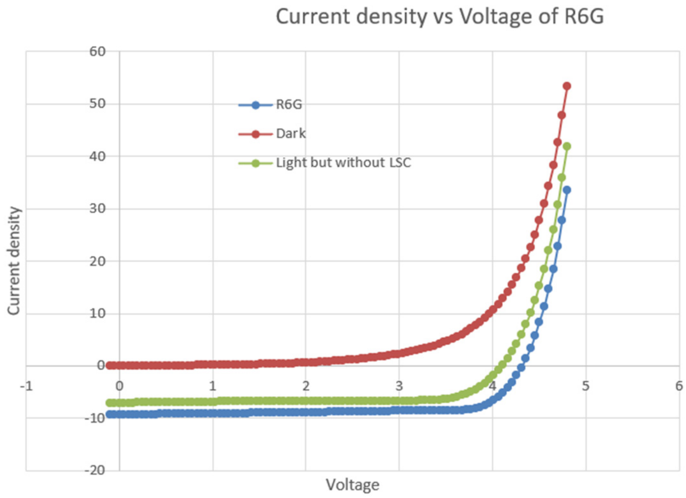
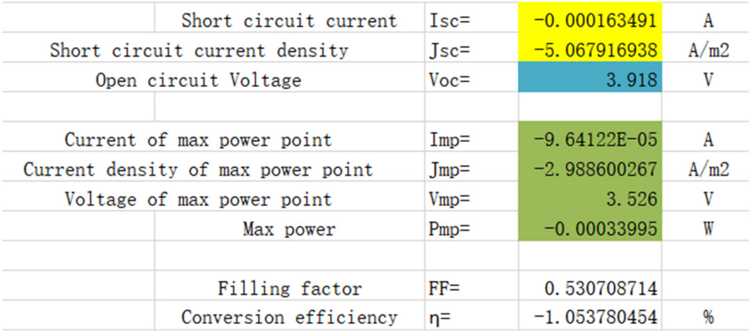


Figure 24. Comparison between dark, with and without LSC JV curves (R6G)

4.4.3. C6 (Green)

4.4.3.1 Result



Short circuit current	Isc=	-0.000163491	A
Short circuit current density	Jsc=	-5.067916938	A/m2
Open circuit Voltage	Voc=	3.918	V
Current of max power point	Imp=	-9.64122E-05	A
Current density of max power point	Jmp=	-2.988600267	A/m2
Voltage of max power point	Vmp=	3.526	V
Max power	Pmp=	-0.00033995	W
Filling factor	FF=	0.530708714	
Conversion efficiency	η=	-1.053780454	%

Figure 25. Energy conversion efficiency of C6 sample

4.4.3.2 Power Density vs Voltage

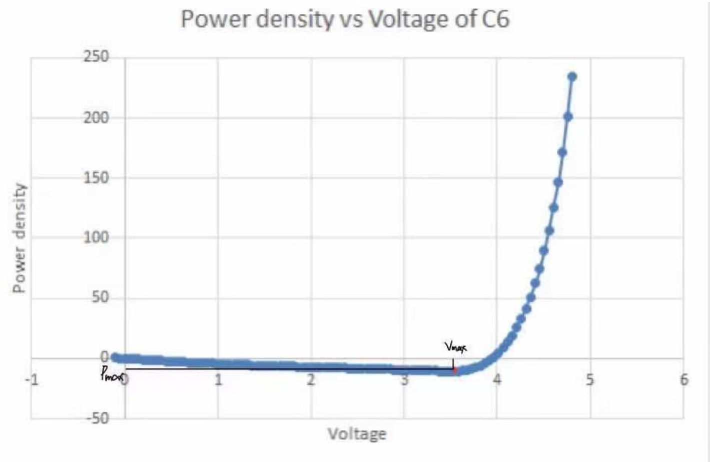


Figure 26. PV curve of C6 sample

4.4.3.3 IV Curve

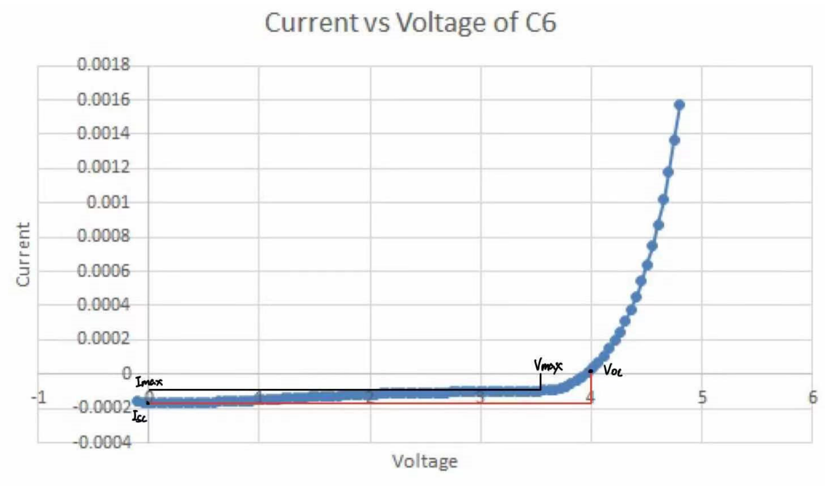


Figure 27. IV curve of C6 sample

4.4.3.4 JV Curve

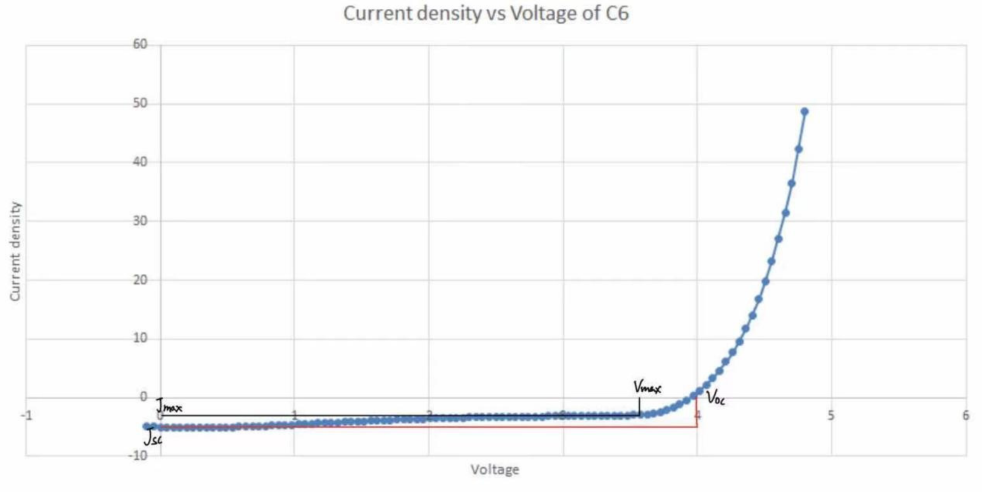


Figure 28. JV curve of C6 sample

4.4.3.5 Comparation between Dark, with and Without LSC

Comparing the I-V diagram and J-V diagram of LSC, Dark and Light reference, it can be found that the area enclosed by I_{sc} (J_{sc}) and V_{oc} of the Dark group is particularly small, while the area enclosed by I_{sc} (J_{sc}) and V_{oc} of the Light reference is larger than that of the Dark group. The group is larger, but smaller than the LSC group (only the third quadrant is considered). This proves the light-gathering effect of LSC.

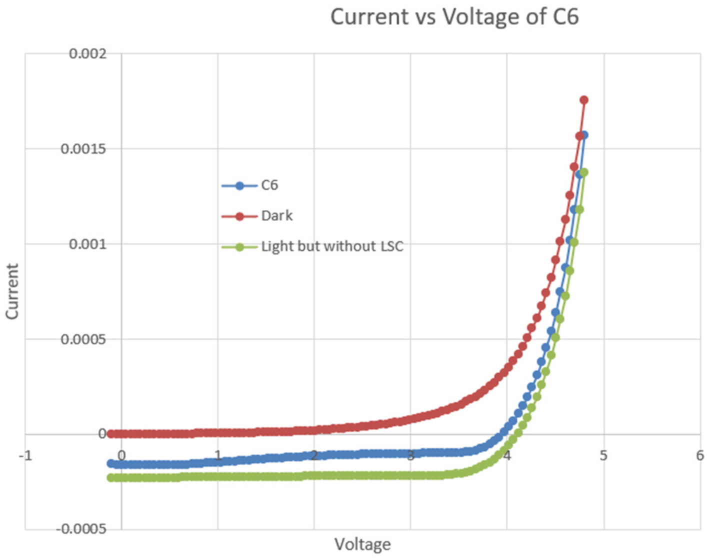


Figure 29. Comparison between dark, with and without LSC IV curves (C6)

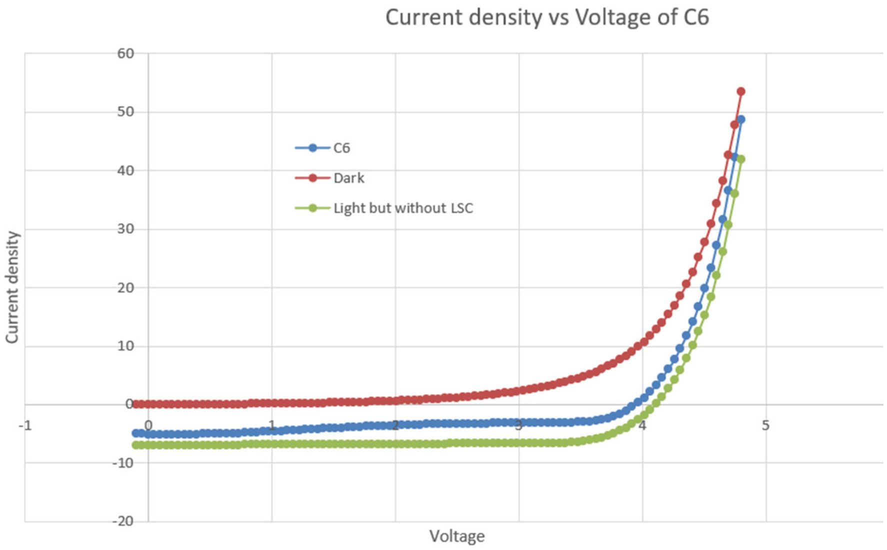


Figure 30. Comparison between dark, with and without LSC JV curves (C6)

4.4.4. Comparation

Table 4. Comparation (4)

	J_{sc} (A/m^2)	V_{oc} (V)	FF	$\eta_{conversion}$ (%)
RBB (Red)	-7.57	4.114	0.4852	-1.51
R6G (Orange)	-9.33	4.310	0.7758	-3.12
C6 (Green)	-5.07	3.918	0.5307	-1.05

5. DISCUSSION

5.1. Preparing Process

In the process of preparing LSC, the reasons why the sample becomes soft are:

a. The ratio of resin and hardener is wrong, resulting in softness

b. Ethanol is not completely removed.

5.2. Stoke Shift

Stokes displacement is a crucial factor in LSC. Stokes shift refers to the difference between the wavelength of light re-emitted by a fluorescent material after light is absorbed and the wavelength of the absorbed light. This shift has a profound impact on the performance of the LSC and needs to be balanced in the design and selection of fluorescent materials to optimize overall system efficiency.

For RBB, Stoke Shift is 78.179nm. For R6G, Stoke Shift is 65.834nm. For C6, Stoke Shift is 65.834nm. In comparison, RBB has a larger Stoke Shift, which means it has a larger energy gap, which means it has a larger photoelectric conversion efficiency.

A larger Stokes shift helps reduce light reabsorption, which is beneficial to improving photoelectric conversion efficiency. After the light is absorbed, the re-emitted light has a longer wavelength, which is more conducive to avoiding being absorbed again by the fluorescent material. This minimizes light loss and increases energy capture efficiency.

However, an excessively large Stokes shift may cause the wavelength of the emitted light to deviate from the high-energy region of the solar spectrum. This may affect the overall energy capture efficiency, as high-energy light regions of sunlight may not be efficiently absorbed and re-emitted by the fluorescent material.

When selecting fluorescent materials, these two considerations need to be weighed to find the right balance. Therefore, when designing and optimizing LSC systems, the magnitude of the Stokes shift needs to be carefully considered to ensure that the overall energy capture efficiency is not significantly reduced while improving the photoelectric conversion efficiency. This requires in-depth research and experimentation to find the most suitable fluorescent materials and LSC system designs for specific applications.

5.3. External Quantum Yield

External quantum yield refers to the rate at which a system absorbs energy from an external field per second and converts it into useful internal energy under the influence of an external field. It is usually expressed as the ratio of the amount of energy absorbed by the system from the external field per unit time to the time. In this experiment, since each side of the LSC transmits light, it is very difficult to individually measure the EQY on the side of the LSC. Therefore, the method adopted is to first measure the overall EQY, then blacken the sides, measure the Top and Bottom EQY, and finally subtract the two to obtain the side EQY.

5.4. Concentration Factor, C

The concentration coefficient is defined by formula $C = M \times \eta_{opt}$,

$where\ M = \frac{Top\ Area}{Sides\ Area}\ and\ \eta_{opt} = \text{Ext. quantum yield of Sides (\%)}$.

Therefore, under a fixed M, the larger the EQY of Sides, the larger C.

The concentration factor of an LSC is defined as the photon flux density at the input and the edges of the LSC. A higher concentration factor increases the ability to deliver light to the photovoltaic cell, potentially increasing power output. However, the path length inside the concentrator is long and photons are lost as they pass through. Hence, we need to find a balance between the two. The concentration factor helps evaluate the efficiency and practicality of LSC designs. In addition, the EQY before blackening cannot be compared, because although the Total EQY of some materials is high, the top and bottom transmit more than the sides. And that's not what we want.

5.5. I-V, J-V

I-V testing is a basic evaluation in photovoltaic research to determine the electrical characteristics of photovoltaic cells, such as maximum power point, short-circuit current, and open-circuit voltage. This test provides quantitative data on how effectively LSC improves the performance of photovoltaic cells under various lighting conditions. Performing I-V testing is essential to directly evaluate the performance of photovoltaic cells when combined with LSC.

In this experiment, by analysing the Power density vs Voltage, I-V and J-V images of different optical materials, it can be found that the J_{sc}, V_{oc}, FF and $\eta_{conversion}$ of R6G are larger than the other two groups. However, this is somewhat different from the theory in the literature. In theory, C6 should have the greatest conversion efficiency. he possible reasons are that the bubbles in the optical material were not removed during production and the mold was uneven.

Comparing the I-V diagram and J-V diagram of LSC, Dark and Light reference, it can be found that the area enclosed by I_{sc} (J_{sc}) and V_{oc} of the Dark group is particularly small, while the area enclosed by I_{sc} (J_{sc}) and V_{oc} of the Light reference is larger than that of the Dark group. The group is larger, but smaller than the LSC group (only the third quadrant is considered). This proves the light-gathering effect of LSC. For RBB, the curve of the Light reference group is very close to that of the RBB group, which may be due to design defects (uneven or bent surface).

6. CONCLUSION

The first part of this experiment, LSC, was successfully fabricated, and the optical properties of three LSC materials (RBB, R6G and C6) were measured in many aspects.

6.1. Stoke Shift

Table 5. Stoke Shift

	RBB (Red)	R6G (Orange)	C6 (Green)
$\Delta\lambda$ (nm)	78.179	65.834	53.043

For RBB, Stoke Shift is 78.179nm. For R6G, Stoke Shift is 65.834nm. For C6, Stoke Shift is 65.834nm. In comparison, RBB has a larger Stoke Shift, which means it has a larger energy gap, which means it has a larger photoelectric conversion efficiency.

6.2. EQY

Table 6. EQY

	Ext. quantum yield of All (%)	Ext. quantum yield of Top and Bottom (%)	Ext. quantum yield of Sides (%)
RBB (Red)	30.181	10.452	19.729
R6G (Orange)	32.003	22.600	9.403
C6 (Green)	53.364	12.781	40.583

Where the C6 has the largest of EQY of sides, which is 40.583%.

6.3. Concentration Factor

Table 7. Concentration Factor

	RBB (Red)	R6G (Orange)	C6 (Green)
Concentrating factor, C	4.011	1.625	3.628

For concentration factor, we can find that RBB has the largest value, which is 4.011.

6.4. Conversion Factor

Table 8. Concentration Factor

	J_{sc} (A/m^2)	V_{oc} (V)	FF	$\eta_{conversion}$ (%)
RBB (Red)	-7.57	4.114	0.4852	-1.51
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C6 (Green)	-5.07	3.918	0.5307	-1.05

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Comparing the I-V diagram and J-V diagram of LSC, Dark and Light reference, it can be found that the area enclosed by I_{sc} (J_{sc}) and V_{oc} of the Dark group is particularly small, while the area enclosed by I_{sc} (J_{sc}) and V_{oc} of the Light reference is larger than that of the Dark group. The group is larger, but smaller than the LSC group (only the third quadrant is considered). This proves the light-gathering effect of LSC. For RBB, the curve of the Light reference group is very close to that of the RBB group, which may be due to design defects (uneven or bent surface).

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