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**Lifetime and Efficiency Improvement
of Organic Luminescent Solar
Concentrators for Photovoltaic
Applications**

By

Yamna El Mouedden

A thesis submitted in fulfilment of the requirements for
the degree of
Doctor of Philosophy

At

Electron Science Research Institute
School of Science

Edith Cowan University

Principal Supervisor: Prof. Kamal Alameh

Principal Co-Supervisor: Dr. Baofu Ding

April 2016

Dedication

To my parents Ali and Fatima, to my brother Ahmed, to my beloved husband Amine and to my family.

DECLARATION

I, Yamna El Mouedden, hereby declare that the thesis “Lifetime and Efficiency Improvement of Organic Luminescent Solar Concentrators for Photovoltaic Applications” is my own original work and that all sources have been accurately reported and acknowledged, and that this document has not previously in its entirety or in part been submitted at any university in order to obtain an academic qualification. I also grant permission for the Library at Edith Cowan University to make duplicate copies of my thesis.

Signature: Yamna El Mouedden

Date: 26-02-2016

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ABSTRACT

In order to achieve the goal of zero net-energy consumption in residential and commercial buildings, substantial research has been devoted to developing methods for energy harvesting from window glass that is capable of passing visible light through the windows of buildings while converting the unwanted invisible solar radiation into electricity. Research has focussed on two particular aspects, namely (i) the integration of thin-film technology for solar radiation transmission control and (ii) light guiding structures for solar radiation routing towards the edges of the glass window.

Recently, photovoltaic (PV) solar cells have been investigated and promoted as products for converting solar energy into electricity. Due to the increased demand for renewable energy sources, the manufacture of PV panels' arrays has advanced considerably. However, they cannot compete with fossil fuel or nuclear energy, due to the high cost of inorganic solar cells and their low power conversion efficiency (PCE).

To lower the cost per installed capacity (\$/Watt) and to use the complete solar spectrum, new PV technologies have been developed, such as solar concentrators. Among the many kinds of concentrators, luminescent solar concentrators (LSCs) have significant industry application potential. Materials used in LSCs are inexpensive, the solar cell size is reduced and no tracking of the sun is required.

In an LSC, the incident sunlight is absorbed by luminescent species, such as fluorescent dyes, quantum dots or rare-earth ion embedded in the active layer (organic or inorganic), which re-emits light in random directions usually at longer wavelengths. In an ideal LSC, all the re-emitted light can be routed towards the edges, where the attached small-area solar cells harvest the light and convert it into electricity.

In this thesis, several contributions are made toward the development of organic LSCs. The first contribution is related to the design and development of multilayer thin film structures containing dielectric and metal layers, using physical vapour deposition, for the control of thermal and solar radiation propagated through glass windows. Measured transmittance spectra for the developed thin-film structures are in excellent agreement with simulation results.

For the second contribution, a cost-effective, long-life-time organic LSC device with UV epoxy as a waveguide layer doped by two organic materials is developed. A PCE as high as 5.3% and a device lifetime exceeding 1.0×10^5 hrs are experimentally achieved.

The third contribution of the thesis is the development of a general method for encapsulating organic LSCs, based on employing three optically transparent layers, (i) an encapsulating epoxy layer and (ii) two insulating SiO_2 layers that prevent the dye dissolving into the epoxy layer. The encapsulated organic LSCs demonstrate an ultra-long lifetime of $\sim 3.0 \times 10^4$ hrs and 60% transparency when operated in an ambient environment, of around 5 times longer than that of organic LSCs without encapsulation.

Finally, the last contribution of the thesis is the development of a new LSC architecture that mitigates the reabsorption loss typically encountered in LSCs. Experimental results demonstrate significant reduction in photon reabsorption, leading to a 21% increase in PCE, in comparison with conventional LSCs.

LIST OF PUBLICATIONS

➤ **Conference paper:**

Yamna El Mouedden, Ramzy Alghamedi, Nur E. Alam, Mikhail Vasiliev, Kamel Alameh.

Electron Science Research Institute, Edith Cowan University, 270 Joondalup Drive, Joondalup, WA, 6027, Australia.

‘Thin film coatings for solar and thermal radiation control prepared by physical vapour deposition’, High-capacity Optical Networks and Enabling Technologies (HONET), 2012, 9th International Conference.

➤ **Scientific papers:**

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‘A cost-effective, long-lifetime efficient organic luminescent solar concentrator’, Journal of Applied Physics, 2014.

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'Encapsulation of Tandem Organic Luminescence Solar Concentrator with Optically Transparent Triple Layers of SiO₂/Epoxy/SiO₂', IEEE Journal of Selected Topic in Quantum Electronics, vol. 22, no. 1, January/February 2016.

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'Dye region partitioning for reabsorption loss mitigation in luminescent solar concentrators', Journal of Applied Physics, March 2016.

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CHAPTER 1

1- AIMS AND STRUCTURE OF THE THESIS

1.1- AIMS OF THIS THESIS

One of most promising technologies for producing energy from clean and renewable sources is the photovoltaic (PV) technology. Due to the increased demand for renewable energy sources, the manufacturing of solar cells and PV arrays has advanced considerably. However, conventional silicon-based PV panels which have dominated the PV market, cannot compete with fossil fuel or nuclear energy, due to the high cost of inorganic solar cells and their low power conversion efficiency (PCE) [1]. Alternatives to the expensive PV panels are new materials and technologies, which in recent decades have gained increasing attention, especially organic polymers and small molecules, due to their low cost and flexibility. Because of these benefits, they have been trialled for use in polymer-based organic PV and in organic luminescent solar concentrators (LSCs).

Typically, LSCs are made of a transparent substrate with luminescent particles deposited as a thin film coating on top of the substrate. In general, the waveguide plate in an LSC is polymer poly-methyl-methacrylate (PMMA), or an epoxy layer that has a higher refractive index than that of the air. Because of the difference between the refractive indices of the air and the polymer, the emitted light is trapped and guided toward the edge through total internal reflection [2, 3]. The luminescent dyes in LSCs act as light converters that absorb certain wavelengths of the sunlight and emit light at longer wavelengths. A fraction of the emitted light is directed towards the edges of the plastic plate where PV cells are attached to convert light into electricity [4].

The main advantage of LSCs is that both direct and diffused light are absorbed, therefore no sun-tracking system is required, thereby reducing installation costs. LSCs utilise a wide choice of inexpensive materials and can be

flat or flexible devices. There is the possibility of breaking down the solar spectrum into segments and concentrating them simultaneously, stacking plates containing dyes with different absorption characteristics, and matching them with different solar cells [5, 6]. An LSC could be suited for building integrated Photovoltaic (BIPV) applications [7, 8] as shading devices or active building facades. However, the LSC with luminophores, does suffer from photo-degradation, oxygen exposure and moisture, which gives them a limited lifetime. Sometimes, this is readily overcome by encapsulation, purification, choice of the host material and the photo resistance of new dyes. Nonetheless, it is still a serious parameter that must be considered in the design of BIPV systems.

The absorption range for LSCs is often limited, and this in turn limits the percentage of solar spectrum that can be exploited by the PV cells. Most of the LSCs get a major loss of re-emitted photons because of the reabsorption losses due to often a small Stokes shift (i.e. the difference in wavelength between the absorption and the emission peak). Reabsorption loss is one of the major loss mechanisms, it describes the probability that an emitted photon will be reabsorbed by another luminescent molecule and the chances of not being re-emitted are big, eventually leading to a minimum percentage of photons reaching the solar cells. Several approaches have been employed for avoiding the reabsorption loss in LSCs, including 1) synthesizing new material with large Stoke's shift [9, 10], 2) developing the resonance shifting structure to reduce the absorption and emission spectra overlap [11, 12], and 3) using excitation energy transfer from an aggregation-induced emitter to efficiently harvest light [4, 13, 14]. However, the reabsorption loss is still a key issue in LSCs, and hence, more research work is needed to mitigate its impact on the PCE of LSCs.

1.2- STRUCTURE OF THIS WORK

This thesis is structured as follows:

- **Chapter 1** highlights the aims of this PhD project.
- **Chapter 2** discusses the importance of and the recent progresses in the renewable energy technologies. The LSCs are introduced as well as their principle of operation is described in detail.

- **Chapter 3** presents the different parameters for LSC fabrication, such as the choice of the host material, the choice of organic materials and the selection of solar cells. The thin film coating structure, including the dielectric and metal layers are discussed, as well as the fabrication process for organic thin film deposition, namely thermal evaporation and spin coating.
- **Chapter 4** presents the results reported in a peer-reviewed IEEE conference paper, entitled “Thin Film Coatings for Solar and Thermal Radiation Control Prepared by Physical Vapour Deposition”, published in the HONET conference proceedings in 2012, IEEE [15]. The paper details the development of the structure of the thin film layer used to control the thermal and solar radiation transmitting through a glass window. Specifically, metal-dielectric multilayer structures reflecting UV, near-infrared and thermal radiations, whilst maintaining a maximum transmission in the visible range are prepared using both an E-Beam and Thermal evaporator and an RF Magnetron sputtering system. In addition, a thin film structure, giving consideration to environmentally stable coatings that can be fabricated easily and can compete with current industry-leading energy-saving glazing products, is discussed.
- **Chapter 5** comprises results reported in the first published journal article, entitled “A cost-effective, long-lifetime efficient organic luminescent solar concentrator”, which appeared in the Journal of Applied Physics, in 2014 [16]. The main research contribution of this article is that an organic LSC can be developed based on the use of an optically transparent lamination layer comprising a blend of an organic semiconductor host material, Alq₃, and an organic red dye, DCJTB, which is sandwiched between two glass panes. Experimental results demonstrate that the developed organic LSC can achieve a PCE of up to 5.3% and a lifetime of > 1.0×10⁵ hrs when operated in ambient environments.
- **Chapter 6** presents the results reported in the second published journal article, entitled “Encapsulation of tandem organic luminescence solar concentrator with optically transparent triple layers of SiO₂/epoxy /SiO₂”, which appeared in IEEE Journal of Selected Topics in Quantum Electronics, VOL. 22, NO. 1, January/February 2016. In this journal article, a tandem organic LSC is encapsulated and connected with three optically transparent layers, namely, an encapsulating epoxy layer and two insulating SiO₂ layers that prevent the organic dyes dissolving into the epoxy layer. Experimental results demonstrate that the encapsulated organic LSC maintains high average transmission of 60% in the

visible range [390-700] nm, and has an ultra-long lifetime of $\sim 6.7 \times 10^4$ hrs under illumination tests in laboratory environments.

- **Chapter 7** presents the results reported in a manuscript, which has been submitted for publication to the scientific journal “Solar Energy materials and Solar Cells”. The manuscript is entitled “Dye region partitioning for reabsorption loss mitigation in luminescent solar concentrators”. In this manuscript, a new LSC structure is introduced, which comprised two dye regions, capable of mitigating the problem of reabsorption losses. Here, we demonstrate a general, simple but powerful way to overcome this problem by employing a partitioning structure, in which red and green fluorescent dyes are doped in the internal central square and the surrounding frame-shape zones, respectively. Selected dyes filled form the following criteria: (i) high PL quantum yield, (ii) no overlap between red-dye emission and green-dye absorption spectra and (iii) full embedment of green-dye emission spectrum in red-dye absorption spectrum. Light emitted by the dye in the centre was observed propagating through the sample toward the edges with minimum reabsorption loss. Based on this structure, the reabsorption loss has been significantly reduced, enabling a 21% increase in PCE compared to that of the conventional LSC.
- **Chapter 8** summarises all the main experimental results obtained in this PhD project and considers possible future research works.

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CHAPTER 2

2- INTRODUCTION

2.1- THE IMPORTANCE OF SOLAR ENERGY

Throughout centuries, mankind has tried to generate energy from many sources, and the sun is one of them. The sun, although a distance of more than 150 million kilometres from earth, remains our greatest source of energy, even though it is intermittent. This solar energy is clean, easily accessible and virtually inexhaustible. In total, the power generated from the sun is approximately equal to 3.8×10^{26} W per second [1], but only a small fraction of this energy reaches the surface of the earth (1.0×10^{17} W on average) [1]. The International Energy Agency IEA estimated that in 2012 the world energy consumption was 155,505 terawatt-hour (TWh) [2].

Research organisations and industries are investing in renewable energy and working hard to harvest solar energy using viable methods and techniques, especially those based on the PV effect. The main motivation is that in a few decades the reserves of carbon-based fossil fuels on earth will be depleted and it will be necessary to develop renewable resources as much as possible. Another important motivation is that if solar energy development becomes sufficient for the world energy demand, there will be a considerable reduction in global pollution and CO₂ emissions which are mainly caused by burning fossil fuels [3].

There are different ways of converting solar energy into electricity: (1) PV inorganic or organic panels, where cells convert sunlight directly into electricity, the majority of solar cells are made of silicon material. As photons from the Sun hit PV cells, they separate electrons from their atoms, allowing them to flow through the material, thus creating electricity. (2) Concentrating solar power (CSP) plants, which produce electric power by converting the Sun's energy into high-temperature

heat, using various mirror configurations [4]. The heat is then channelled through a conventional generator. There are four CSP technologies being promoted internationally. The amount of power generated by a CSP plant depends on the amount of direct sunlight. Like concentrating PV concentrators, these technologies use only direct-beam sunlight, rather than diffuse solar radiation. The first CSP technology is based on using Parabolic Trough Collectors, formed using sheet of reflective materials into a parabolic shape that concentrates incoming sunlight onto a central tubular receiver at the focal point of each collector [5]. The second CSP technology is the Linear Fresnel Reflector, which uses a field of long linear mirror strips to concentrate light on a fixed linear receiver [6]. The mirrors rotate to track the Sun. The third technology is the Paraboloidal Dish Concentrator, which is composed of a frame in the shape of a parabolic dish, where curved mirrors are placed to concentrate solar radiation onto the focal point of the dish [7, 8]. The fourth technology is the Power Towers, which is a ground-based field of mirrors that focus solar radiation onto a receiver mounted high on a central tower [9].

Depending on the technology, the electricity cost is between 0.8-2 euro/Wh, which is still very far from the electricity cost generated by conventional fossil-fuel energy, which is around ~0.04 Euro/kWh in some European countries [10]. Thus, a new alternative approach to lower the costs of PV needs to be developed to shrink the gap between the cost of electricity generated by fossil fuel and renewable sources. Many researchers are currently working on developing efficient solar concentration technologies to replace the expensive CSP technologies or solar-cells. To reach a lower cost per installed capacity (\$/Watt) and to use the complete solar spectrum, new solar concentrators have been developed, based on employing waveguiding structures to concentrate large-area solar light onto small-area solar cells. Among the many kinds of solar concentrators, luminescent solar concentrators (LSCs), (illustrated in Figure 1), have a significant potential in industry applications, in comparison with other conventional light concentrators, which require focusing lenses as well as expensive sun-tracking equipment, thus losing the simplicity of the flat solar panel [11]. Also, LSCs can be utilised for infrastructure-integrated PV applications, where buildings produce their own energy supply.

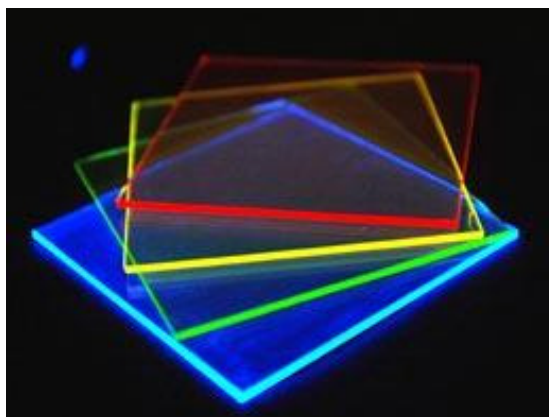


Figure 1: Picture of LSCs device (source: Donna Coveney, MIT)

Figure 2 shows the estimated cost per Watt for four main PV devices, namely, organic solar cells, crystalline Si cells, Thin-film-based PV cells and LSCs [13]. It is obvious that LSCs are economically attractive compared to their counterparts [11, 12], however, their efficiency is the lowest.

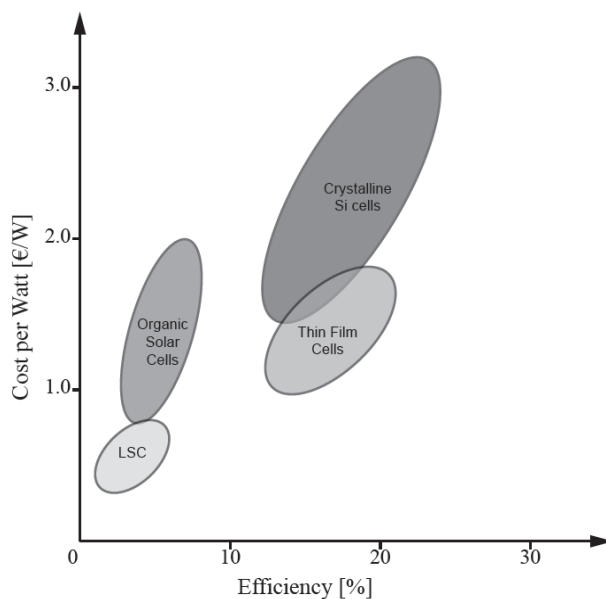


Figure 2: Diagram showing the estimated cost per watt of various solar conversion systems as a function of efficiency [13].

In the next part of the chapter, a description of an LSC and its operation principle will be presented, and the attractiveness of LSCs in the field of renewable energy will be discussed.

2.2- LUMINESCENT SOLAR CONCENTRATORS: PRINCIPLE, LSC PERFORMANCE AND LOSS MECHANISMS

LSCs have unique features that make them attractive for BIPV applications. These features include (i) the inexpensive materials used to construct them, (ii) the small size (and hence low cost) of the solar cells needed to convert the concentrated light into electricity, and (iii) they require no tracking of the Sun. In the 1970s, Lerner [14], Weber and Lambe [15] proposed a method to concentrate sunlight into a small area using LSCs. Since then, the power efficiency of LSCs has been promoted considerably. For example, in the 1980s, 4.0% of power efficiency was achieved by Wittwer et al. [16, 17]. In 2008, L. H. Slooff et al., developed an LSC with a PCE equal to 7.1% [18], measurement made at European Solar Test Installation laboratories. Then in 2010, the efficiency was increased to 12% by Dienel et al. [19].

2.2.1- Luminescent Solar Concentrator Principle

The active layer in a conventional LSC (illustrated in Figure 3) is realised by embedding inorganic or organic luminescent particles [11, 20-22] in organic insulating hosts. In an LSC, the incident sunlight is absorbed by these luminescent molecules, emitting light at longer wavelengths in random directions. It is expected that in an ideal LSC, all of the emitted light can be routed (or guided) towards the edges, where the attached, small-area solar cells harvest the light and efficiently convert it into electricity. A high concentration factor enables LSCs to use solar cells of smaller areas, and hence can reduce their costs substantially [11, 23-25].

The key component in an LSC is the waveguide material, called the host material. The host material is usually a transparent polymer film (e.g. poly-methyl-methacrylate PMMA [22]), doped by nano-particles, quantum dots [26, 27] or luminescent dyes [12, 23, 27-30]. These particles absorb the incident photons and re-emit photons at longer wavelengths, as shown in Figure 3. Due to a high refractive index of the transparent polymer plate, a large proportion of the emitted photons are trapped inside the polymer layer and guided toward the edges. Consequently the small-area inorganic solar cells, attached to edges, harvest these photons and convert them to electricity [19, 31].

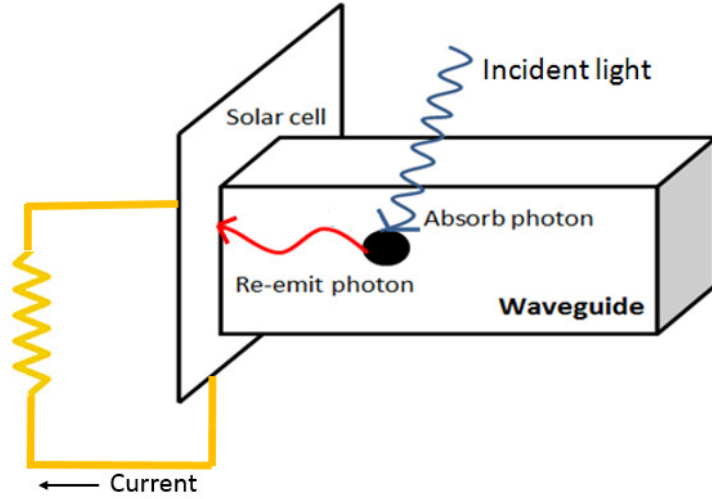


Figure 3: Schematic representation of incident sunlight entering the waveguide and absorbed by a luminescent molecule (black dot). The light is re-emitted at a longer wavelength and a fraction of the emitted light is trapped inside the polymer layer due to the total internal reflection [32].

Snell's law of refraction describes the transport of light-rays when they pass through a sharp interface between a transparent dielectric medium t and medium i , as shown in Figure 4(a). According to this law of refraction, the incident angle θ_i and refractive angle θ_t ray in Figure 4(a) should satisfy the following formula:

$$n_i \sin \theta_i = n_t \sin \theta_t \quad n_i \sin(\theta_i) = n_t \sin(\theta_t) \quad (1)$$

The ratio between the number of trapped re-emitted photons and the number of escaped re-emitted photons is determined by the ratio n_t/n_i . When the incident angle of the emitted light from luminescent dyes reaches the critical angle (see Figure 4(b)), the refractive angle θ_t is 90° . Since n_t is usually the refractive index of air (~ 1.0), the critical angle can be written as [25]:

$$\theta_c = \sin^{-1}(1/n_i) \quad (2)$$

By further increasing the incident angle to be higher than this critical angle, as shown in Figure 4(c), the emitted light will be totally reflected in the LSC structure, trapped and routed toward the edges.

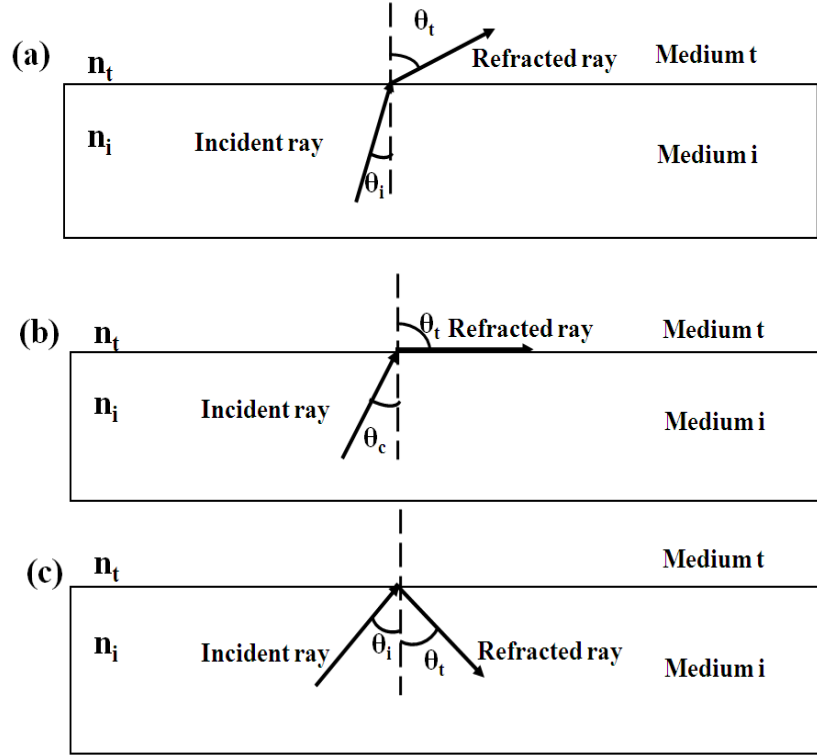


Figure 4: Illustration of the refraction of light at the interface between two different media for three different refracted ray angles: (a) refraction, (b) refraction at critical angle, (c) total internal reflection.

2.2.2- LSC Performance

The performance of LSCs is mainly assessed by the optical efficiency (η_{opt}), which is expressed as Goetzberger Equation (3) [19, 25, 33-35]:

$$\eta_{opt} = (1-R)P_{TIR} \cdot \eta_{abs} \cdot \eta_{PLQY} \cdot \eta_{Stokes} \cdot \eta_{host} \cdot \eta_{self} \quad (3)$$

The significance of each efficiency term of Equation (3) is described as follows:

- (1-R) is the fraction of incident light transmitted into glass panes of LSCs excluding a small loss of incident light due to Fresnel reflection from the front

surface of the glass. The reflectivity is given by the usual expression $R = (n-1)^2 / (n + 1)^2$, for example, for a waveguide matrix with a refractive index equal to $n=1.5$, the reflectivity is around 4%.

- Probability of total internal reflection (P_{TIR}); part of the light absorbed is emitted inside the escape cone, thus leaving the LSC. Light emitted is trapped inside the LSC when it strikes the internal surface of the sheet at an angle greater than the critical angle. The critical angle, θ_c can be calculated from Equation (1).

The LSC trapping efficiency is given by [19, 36]:

$$P_{TIR} = \frac{\sqrt{n^2-1}}{n} \quad (4)$$

Therefore, for $n=1.5$ (PMMA and glass) $P_{TIR}=0.75$. This means approximately 75% of the light emitted will be trapped by total internal reflection, and 25% will be lost through refraction to the air. This loss mechanism is amplified with the presence of optical reabsorption, because light emitted from subsequent reabsorption events also has a 25% probability of being lost in one of the escape cones. It is difficult to avoid photon escaping the LSC, as it completely depends on the refractive index of the material used as a waveguide, which is in the range of $n=1.3-1.5$.

- η_{abs} is the absorption efficiency. The doping dyes in an LSC sheet usually absorb a narrower range of wavelengths and emit light at longer wavelengths. To obtain high power output, luminophores materials should be able to absorb the greatest possible range of incident solar wavelengths and emit photons at energies greater than the band gap of the solar cells. For example, for an ideal LSC performance with silicon cells, the active layer should absorb all wavelengths <950nm and emit in the 950-1000nm range, which corresponds to the spectral range at which the responsivity of the silicon solar cell is maximum [37].

- η_{PLQY} is the photoluminescent quantum yield (also called the luminescent quantum efficiency (LQE) or quantum yield (QY)), which is the number of photons emitted per absorbed photon, and is given by [38, 39]

$$\eta_{PLQY} = \frac{N_{em}}{N_{abs}} \quad (5)$$

Eventually, high LSC performance is achieved if the luminescent particles have a high photoluminescent quantum yield near 100%.

- η_{Stokes} is the Stokes efficiency. In the luminescence process, the emitted photon has a longer wavelength (lower energy) than the absorbed photon; consequently energy is lost during the luminescence process. Since this is a natural phenomenon of the wavelength-shifting process, which occurs in an LSC, it is always present and η_{Stokes} will be equal to 0.75.

- η_{host} is the efficiency of the host absorption. One possible loss mechanism is absorption of trapped light by the host material. Most polymers and glass materials, which are used for LSCs are highly transparent in the visible range. However, the concern for this loss mechanism will be more at the near-infrared range, namely, above 700 nm.

- η_{self} self-absorption. This efficiency applies only to the fraction of luminescence photons reaching the edges of the LSC sheet without being lost due to reabsorption. Reabsorption occurs when emitted photons are reabsorbed by other luminescent molecules [36, 40]. Typically, if there is reabsorption, the absorption and emission spectra overlap. The reabsorption of photons mainly occurs with organic dyes (fluorescent dyes) or quantum dots. The separation between the peak absorption and emission wavelengths is called the Stokes shift. This efficiency is the ratio between the emitted photon energy and the absorbed photon energy. Figure 5 illustrates the concept of Stokes' shift by displaying the absorption and emission spectra for a typical fluorescent dye.

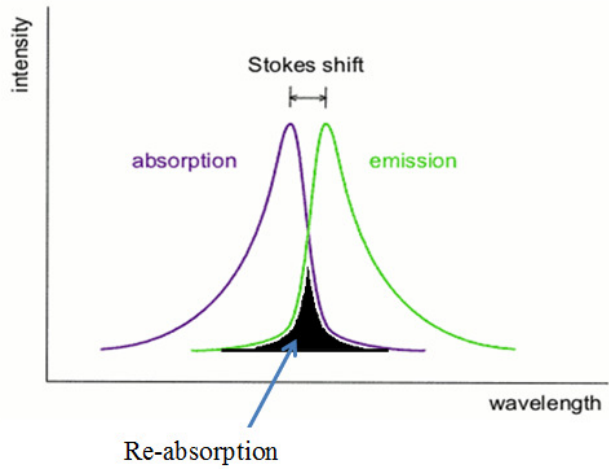


Figure 5: Diagram illustrating a typical absorption and emission spectra of a fluorescent dye.

2.2.3- Loss Mechanisms

Up to now, LSCs still have low PCE, mainly due to several optical loss processes. The key loss processes, which are illustrated in Figure 6, include: (i) insufficient solar light absorption, (ii) high optical absorption of the host, linked to the efficiency of the host (η_{host}), (iii) low photoluminescence quantum efficiency of luminescent dyes, linked to the η_{PLQY} efficiency, (iv) escape of emitted light, linked to probability of total internal reflection (η_{PTIR}), (v) reabsorption of the emitted light from other dyes, linked to the self-absorption η_{self} efficiency.

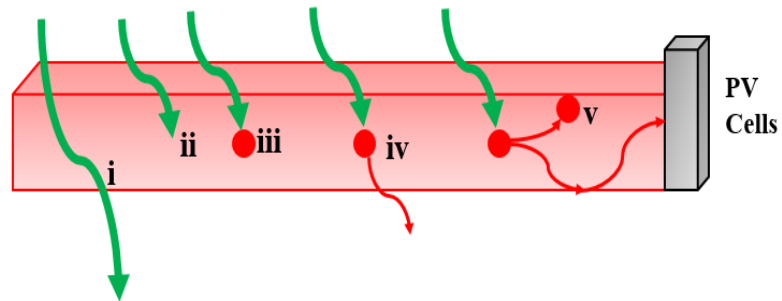


Figure 6: Illustration of the typical loss mechanisms in the cross-section of an LSC. Solar cells are attached to the edges of the sheet to convert the trapped emitted light into electricity. (i) Solar light transmission, (ii) optical absorption of the host, (iii) low photoluminescence quantum efficiency of luminescent dyes, (iv) escape of emitted light through refraction, (v) reabsorption of the emitted light by other dyes.

To reduce the LSC loss mechanisms, researchers have proposed and demonstrated different techniques. The PCE of the LSC can be increased by (i) increasing the probability of total internal reflection (η_{PTIR}), (ii) increasing the absorption of the matrix (η_{host}), (iii) increasing the Stokes efficiency (η_{Stokes}) and (iv) reducing the reabsorption of emitted photons by other molecules (η_{self}).

For η_{PTIR} , it only depends on the refractive index of the matrix, therefore to have the best of PTIR, the doping matrix should have a high refractive index (typically >1.3). Part of emitted light typically escapes from the escape cone, which represents 25-30% of the overall loss [25]. In the last few years, multiple groups have researched minimizing this loss using two main processes: aligning the luminophores [41] and by applying a wavelength-selective mirror at one surface of the LSC in order to reflect the photons, thus preventing them from escaping the LSC structure [42-45]. Figure 7 illustrates the use of wavelength-selective mirrors at the bottom surface of the LSC substrate.

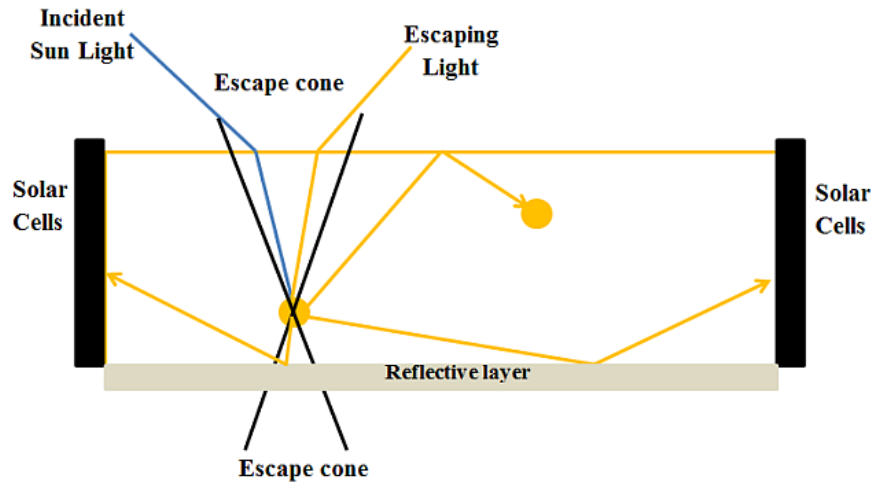


Figure 7: Illustration of an LSC employing a spectrally selective mirror on the surface of the LSC substrate for preventing optical loss through light refraction. Incident light (Blue line) is absorbed by luminescent molecule (yellow dot). The longer-wavelength emitted light (yellow lines) is either guided toward the edges or either reflected by the spectrally selective mirror.

The absorption efficiency (η_{abs}) can be enhanced by using a combination of dyes of different absorption ranges in the LSC active layers [29, 46, 47].

Most luminescent materials used in LSCs have quite small Stokes shifts, leading to a relatively large overlap between the absorption and the emission spectra [36, 48]. A straightforward approach to mitigating the optical reabsorption in LSCs is the design of new luminophores with larger Stokes shifts so that the overlap between the absorption and the emission spectra is minimised. For example, the compound 6,6'- diheptyl[2,2'-bipyridyl]-3,3'-diol (DH-BP(OH)₂) is a fluorescent material that exhibits a large Stokes shift [49]. Some semiconductor (CdSe and PbSe) nanoparticles also have large Stokes shifts, making them potential candidates for LSCs [23, 26, 27, 50].

2.3- PROGRESS IN LSC SAMPLES

Since the late 1970s, researchers developing LSCs have been focussing on enhancing the PCE by reducing the above-discussed loss mechanisms. Since the first LSC proposed in the late 1970s by Lerner, Weber and Lambe, several LSC technologies were reported through the 1980s [51-55], however investigating the commercial viability of LSCs stopped due to the limited choice of luminescent materials at that time. For example, in 1980, Friedman et al. [51] achieved a 3.2% PCE with (14 cm x 14 cm x 0.3 cm) with Silicon cells and 4.5% with GaAs cells. In 1983, Wittwer et al. achieved 4% of PCE for large-area of (40cm x 40cm x 0.3cm), using gallium arsenide (GaAs) solar cells [17]. Recently, J. C. Goldschmidt et al. reported a photonic band stop reflection filter capable of guiding dye-emitted photons within the LSC active layer, thus increasing the LSC efficiency by 20 [42]. In 2008, L. H. Slooff et al. demonstrated a 7.1% PCE using GaAs solar cells for a sample size of 5cm x 5cm x 0.5cm [18]. L. H. Slooff used a diffuse reflector on the rear side of the sample, thus increasing the PCE by 26%. The same year M. J. Currie et al. used both single and tandem-waveguide organic solar concentrators to achieve a PCE of 6.8%, without any reflection filter on the rear surface of the sample [12].

2.4- KEY SCIENTIFIC QUESTIONS AND MOTIVATION OF THE RESEARCH

The key difficulties encountered in the development of LSCs are (i) the short lifetime of the organic dyes and (ii) photon reabsorption. In Chapters 5 and 6, we address the short lifetime problem and propose and demonstrate a new encapsulation method based on using UV-curable epoxy in conjunction with SiO₂ layers that protect the organic dyes, hence increasing their lifetime. In Chapter 7, we address the reabsorption issue and propose and demonstrate a new LSC structure capable of mitigating the reabsorption problem and enhancing the power conversion efficiency by 21%.

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CHAPTER 3

3- FACTORS TO CONSIDER FOR LUMINESCENT SOLAR CONCENTRATOR PRODUCTION

The performance of an LSCs depend on various optical and electrical parameters. Choices of host material (matrix), luminescent particles and PV solar cells are key parameters to consider when designing an LSC device. The size, thickness and shape of an LSC are also important factors that affect the performance, and thus must be taken into consideration. In this chapter, the selection of the matrix, the luminescent materials and the solar cells will be discussed. Also, the micro/nano fabrication and characterisation facilities used for the LSC development and characterization are described.

3.1- WAVEGUIDE MATERIAL, LUMINOPHORES AND SOLAR CELL SELECTION

3.1.1-Waveguide Material Selection

The key function of an LSC is to guide the photons emitted by the dye molecules (luminophores) towards the solar cell attached on the edges for conversion to electricity. Properties, such as refractive index, outdoor lifetime and weight, are important for the waveguide material selection. A key criterion for the waveguide (or host) material selection is to have a low absorption coefficient, so that most of the re-emitted photons can propagate towards the LSC edges with minimum attenuation. According to Snell's law, and as discussed in the previous chapter, a photon is trapped within the waveguide if its propagation angle is larger than the critical angle. Therefore, the selected host material for an LSC must satisfy

two main requirements, namely, a high refractive index and transparency over the emission bandwidth of the luminophores. Poly (methyl methacrylate) (PMMA) [1, 2] or UV epoxy [3] are potential host polymer materials for LSCs, due to their high transparency, adequate refractive index (~1.5) as well as stable chemical properties.

The second role of the host matrix is to act as an isolator material that protects the organic luminophores, which are typically sensitive to oxygen, moisture and UV light [4-6]. Therefore, for practical purposes, an organic LSC device must be encapsulated within adhesive materials exhibiting negligible oxygen and UV light penetration rates and ultralow moisture absorption. However, conventional organic adhesives, including PMMA, do not possess such properties [7, 8]. Among the different adhesives, UV-cured epoxy is a special candidate, which has been widely used as a base material of encapsulating organic light emitting diodes (OLEDs) and organic solar cells (OSCs) [7, 9]. This is because of its extremely fast curing time at room temperatures, and ultra-low water and oxygen permeability as well as strong absorption at UV wavelengths. Accordingly, UV-cured epoxy was adopted for encapsulating the LSC developed throughout the PhD project.

3.1.2- Luminophores Types for LSC Applications

Luminophores in LSC systems are the molecules that absorb the input light and emit photons at wavelengths at which the conversion efficiency of the used solar cells is maximal. For luminophores molecules to be effective, they must meet the following key requirements [10]: 1) should have broad spectral absorption 2) their quantum yield for luminescence should be high (as close to 1 as possible); 3) their Stokes shift should be large enough so that the overlap of the absorption and emission bands is small or negligible; 4) their luminescence wavelength is well-matched to the solar cell spectral response; 5) their absorption coefficient over the input solar spectrum of interest is high and 6) should be cost-effective. Based on these requirements, a large number of luminophores have been explored for LSC applications, which can be divided into three main categories:

1. The quantum dots (QDs) [11-14], which are nanosize semiconducting crystals whose absorption and emission bands depend on their size. They display a wide absorption band, high emission intensity, and a

good photostability [15]. However, they have large overlap of absorption and emission bands, which lead to high reabsorption losses [16] and they have a low LQE [17, 18].

2. Rare earth ions/complexes [19-23], which exhibit high LQE [24], however, they have extremely low absorption coefficients [24].
3. Organic dyes [25-32], which have relatively high absorption coefficients [33] and also high LQE [34-36]. Their main advantage compared to QDs or rare earth ions is that they are easy to process, cost-effective [30] and have a broad range of colours. However, organic dyes often have narrow absorption bands, and among them, some fluorescent dyes have small Stokes-shifts, resulting in high reabsorption losses. Several organic dyes can be mixed in a polymer to reduce losses by optimizing the resonance excitation energy transfer between the dyes [37-39]. Another drawback of organic dyes is that they exhibit photodegradability under exposure to solar radiation, and are sensitive to moisture and oxygen, which shorten their lifetime compared to quantum dot or rare-earth. Nonetheless, the lifetime of organic dyes can significantly be extended by encapsulating them, especially with UV-cured epoxy.

In this thesis, organic fluorescent dyes are selected, mainly because of their high LQEs, good absorption coefficients, their ease of fabrication and their relatively low cost.

3.1.2.1- Organic Semiconductors and Organic Dyes

An organic semiconductor is a compound, in the form of a film, molecular or polymer, which shows similar properties to inorganic semiconductors, such as silicon. These properties include electrical conduction through electrons and holes, and the presence of a HOMO band (for "Highest Occupied Molecular Orbital"), and LUMO (for "Lowest Unoccupied Molecular Orbital"). Organic semiconductors are typically used to develop organic electronic systems and electronic plastics such as OLEDs or OSCs [40, 41]. The main reason for calling them organic materials is because their molecules are carbon-based. The HOMO band is the highest (energy) molecular orbital band occupied by electrons; this is somehow the equivalent of the valence band of inorganic semiconductors. It can be

considered that the position of the highest level of the HOMO relative to the vacuum level corresponds to the energy necessary to oxidize the molecule (Figure 8). The LUMO is the lowest unoccupied molecular orbital band by an electron and is the equivalent of the conduction band of inorganic semiconductors. The energy difference between the two orbital (HOMO-LUMO) can serve as a measure of excitability of the molecule: the greater the energy difference, the less the molecule can be easily excited.

Organic semiconductors have several advantages over inorganic semiconductors, including: (i) lightweight, hence they are more convenient for portability, (ii) flexibility, they conform to the shape of the medium onto which they are deposited, and (iii) low cost, generally they are easy and economical to manufacture in a laboratory. Chemical engineering can develop molecules that self-assemble. These manufacturing methods contrast with the more expensive and complex process technologies inorganic (heating at high temperatures, for example).

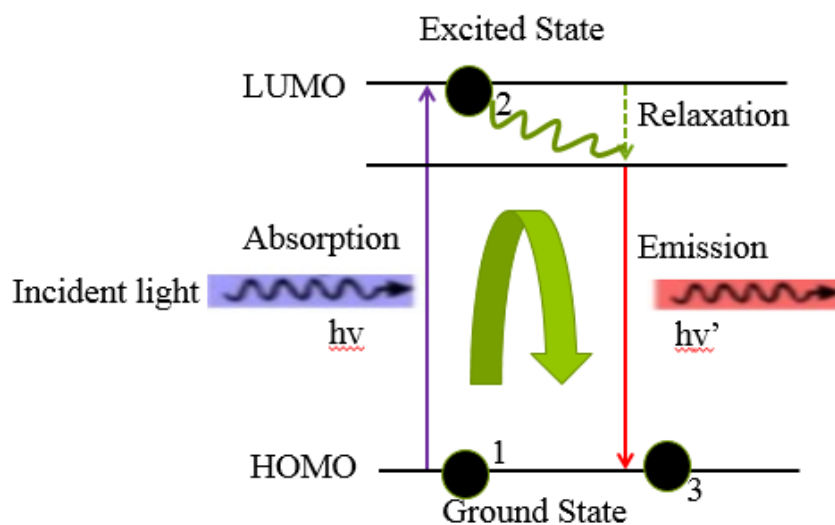


Figure 8: Diagram of the HOMO and LUMO of a molecule. Each representing an electron in an orbit; when light of a high enough frequency is absorbed by an electron in the HOMO, it jumps to the LUMO.

The first selected organic material for LSC development is the semiconductor material tris(8-hydroxyquinoline) aluminium Alq_3 , which has the role of host material in one of the LSC structures, which will subsequently be described. Alq_3 is an organic semiconductor, typically developed in the form of a polymer

film, and has similar inorganic semiconductors properties [42]. Alq₃ has been used for electronic applications such as OLEDs or OSCs [35, 43-45]. Two more fluorescent organic dyes have been selected: 4-(dicyanomethylene)-2-t-butyl-6-(1,1,7,7-tetramethyljulolidyl-9-enyl)-4H-pyran (DCJTb), denoted as the red dye [46, 47] and 3-(2-Benzothiazolyl)-N,N-diethylumbelliferylamine, 3-(2-Benzothiazolyl)-7-(diethylamino) coumarin (C₆), denoted as the green dye [48].

These three organic materials have been particularly selected because of their high self-absorption ratio (ratio between the total radiation current flowing through the surface of the material and the total current obtained if there were no absorption) [49, 50], their high PLQY, and also because they are commonly used in electroluminescent samples, such as organic LED or solar cells [9, 45, 47, 51].

Figure 9 shows the chemical structure of Alq₃, DCJTb and C₆.

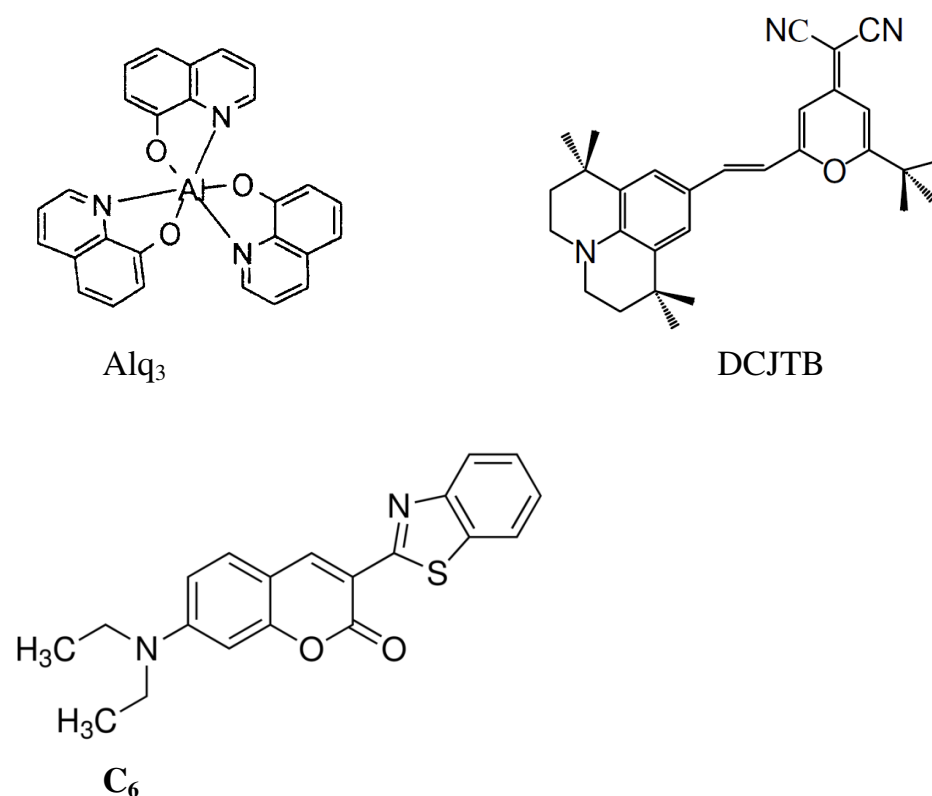


Figure 9: Chemical structure of Alq₃ [47], DCJTb [51] and C₆ [ref: source MP company <http://www.mpbio.com>]

3.1.3- Solar Cells' Selection

It is important for dye molecules doped in a polymer sheet to absorb as much of the incident light as possible, while also matching their emission spectrum with the absorption band of the mounted solar cells, in order to maximize the PCE. Therefore, the solar cells should be selected based on two factors: (i) cost-effectiveness and (ii) matching the emission spectrum of the organic dyes with the incident photon-to-current efficiency (IPCE) of solar cells (in order to maximise the electricity generated by the photons reaching the solar cells).

Crystalline silicon (Si) currently represents about 80% of the market for materials used in the manufacture of solar panels [52]. The band gap of Si (1.11 eV) is very close to the optimal value of ~ 1.3 eV for maximum photo-conversion efficiency [53]. There are two types of crystalline silicon solar cells: monocrystalline cells and polycrystalline cells. The monocrystalline solar cells are the first generation of Si PV cells, typically used in calculators and watches. They are developed from a rod of crystallized silicon. Monocrystalline solar cells are cost-effective, but their production method is laborious and expensive. Polycrystalline solar cells are produced from a silicon block composed of multiple crystals. Their production cost is lower, however, they have a lower efficiency than their monocrystalline counterparts. Technological advances now allow for the production of thin-film polycrystalline or amorphous Si solar cells, thus minimising the use of silicon. Such cells can have a thickness as low as a few micrometres.

Recently, a second generation of thin-film based solar panels adaptable to flexible or rigid substrates has been developed by depositing one or more photosensitive semiconductors and thin films on various substrates such as glass, steel or plastic substrates. Three types of inorganic thin-film solar cells have dominated the market, namely: amorphous silicon, cadmium telluride (CdTe), and copper selenide, indium and gallium (CIGS) [52].

We particularly selected the inorganic polycrystalline Si solar cells for LSC development due to several reasons, namely, (i) their price, compared to monocrystalline cells, and (ii) their incident photon-to-current efficiency (IPCE) perfectly matches the emission spectra of the chosen dyes, hence attaining a high

PCE. The external quantum efficiency spectrum and the emission spectra of C₆ and DCJTb are plotted in Figure 10.

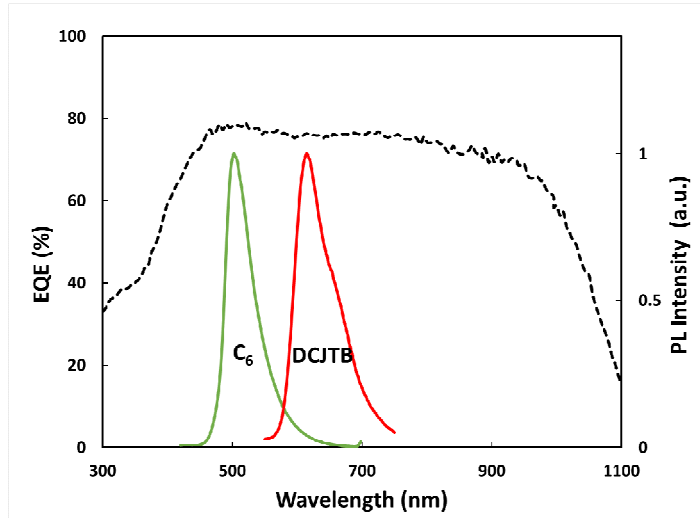


Figure 10: EQE of the selected polycrystalline silicon solar cell and emission spectra of C₆ and DCJTb for all the experiments.

It is important to summarise that the waveguide matrix, the semiconductor materials, and solar cells chosen in this work are U-V epoxy, Alq₃, DCJTb and C₆ and polycrystalline Si solar cells, respectively.

3.2- EXPERIMENTAL SET UP AND CHARACTERISATION

This part of the chapter provides a description of the experimental set up and equipment used during the course of the PhD project. Description of thermal and E-beam evaporator and RF sputtering system utilized to perform deposition of dielectric and metal thin film layers is given, as well as the thermal evaporation system used for organic material deposition. The equipment that were used to characterize the optical and electrical proprieties of LSC are also listed and described.

3.2.1- Thermal and E-beam Evaporator and RF Sputtering System for Metal and Dielectric Thin Film Layers

It is important to note that different deposition techniques can be used for producing thin films of metals, semiconductors or dielectric materials [54]. However, the most common technique is Physical Vapour Deposition (PVD), such as thermal evaporation, e-beam evaporation and RF sputtering [55, 56].

Thin films, made of dielectrics and metals, were grown by all these three methods (RF sputtering and e-beam/thermal evaporation) on unheated glass substrates, with a base vacuum pressure of around 10^{-6} Torr, a growth rate between 0.5-1.5 Å/s, and an Argon (Ar) partial pressure between 1-2 mTorr.

3.3.1.1- E-Beam and Thermal Evaporator

E-Beam and thermal evaporators were used to evaporate or sublimate materials to be deposited on the surface of a substrate (e.g: glass or plastic), in vacuum. By heating the target material at high temperature, the evaporated particles typically propagate in a straight line towards the substrate, whereon a layer is formed. The target material can be evaporated thermally, using a refractory filament (Joule effect), or electron beam energy (E-Beam). The deposition rate depends not only on the temperature of the source and the distance between the crucible and the substrate, but also on the coefficient of adhesion of the evaporated materials onto the substrate. The quality of the deposited thin film depends on the speed with which the particles bind to the substrate during deposition [57, 58].

Evaporation is the easiest deposition method, because it is not necessary to inject a gas to create plasma, while other methods, such as RF sputtering, require PVD plasma as an intermediary. However, the main problem with evaporation is that it is difficult to deposit highly refractive materials at low vapour pressure, and thus the deposited layers may be contaminated through reaction with the various crucibles. In ESRI's cleanroom, a dual thermal/e-beam evaporation system (KVE-ENT 200hl Korea Vacuum Tech, picture in Figure 11), enabled the evaporation in the same vacuum chamber, of up to four different materials, through electron beam evaporation and one additional material via thermal evaporation.



Figure 11: KVE-ENT 200hl Korea Vacuum Tech E-beam and Thermal Evaporator.

3.3.1.2- RF Sputtering System

The sputtering process consists of the bombardment of the target material by fast moving, heavy, inert gas ions from a plasma. The bombarding ions cause atoms to be ejected from the target material by momentum transfer between the colliding ions and the target atoms. Typically the deposited microstructure is compact and amorphous material is obtained. This ion bombardment can also be achieved using an ion gun - this is called IAD technology for Ion Assisted Deposition [59]. It can also be derived from a plasma created in the entire deposition chamber, and is referred to as Ion Plating [60]. In this case, the source material is no longer evaporated, but sprayed, and the material is ablated under the impact of ions, so it is no longer a thermal process, but a transfer of momentum that can give much more energy to the particles to settle. The layers obtained by spraying are naturally high density and have better adhesion. The sputtered atoms are deposited onto the substrates due to the bombardment of the target materials' influence of the ionized gas atoms. The main parameters which relate to thin film deposition onto the substrates using sputtering technology, are the RF power densities, substrate temperature, distance between substrates and target.

ESRI's RF magnetron sputtering system (KVS-T4065 Korea Vacuum Tech, LTD, picture in Figure 12) has two thickness monitors, namely a quartz monitor and a laser reflectometry based monitor, which enable the thicknesses of the various deposited layers to be controlled within ± 2.0 nm accuracy.



Figure 12: KVS-T4065 Korea Vacuum Tech, LTD Sputtering system.

3.2.2- Deposition of Organic Thin Film Layers

Thermal evaporation is employed to deposit the small-molecule organic materials onto a glass substrate in a high vacuum chamber. High-vacuum thermal evaporation particularly has the advantage of forming thin films with very high uniformity [61]. Vacuum thermal evaporation involves heating the organic semiconductor using a resistive heating source under a vacuum environment with a base pressure around 10^{-6} Torr. This technology has been used widely for the fabrication of OLEDs and OSCs [62]. On the other hand, for the polymer layer fabrication, the main techniques used are drop casting, spin coating [61-63] or ink-jet printing [64]. We used spin coating for polymer layer fabrication, where the solution is typically prepared by mixing polymer hosts, luminescent dyes in a solvent. The solution is then stirred for several minutes or hours to dissolve the polymers homogeneously. Subsequently, the solution is spin-coated onto glass substrates. Note that polymers are sensitive to oxygen and moisture, and therefore, a N_2 filled glove box shown in Figure 13 is used to ensure that the spin coating process takes place in the oxygen and moisture free space.



Figure 13: Picture of the Glove box of the Organic thermal evaporator housed in ESRI's cleanroom.

Particularly important to this PhD project, we used a new thermal evaporation system in ESRI's cleanroom. This system comprises 18 thermal evaporation sources (Figure 14), which can be used to deposit up to 6 different organic materials at the same time. A second part of the system comprises an inorganic deposition chamber, six inorganic material can be coated as well, using thermal evaporator process, and up to two different inorganic materials can be deposited at the same time.

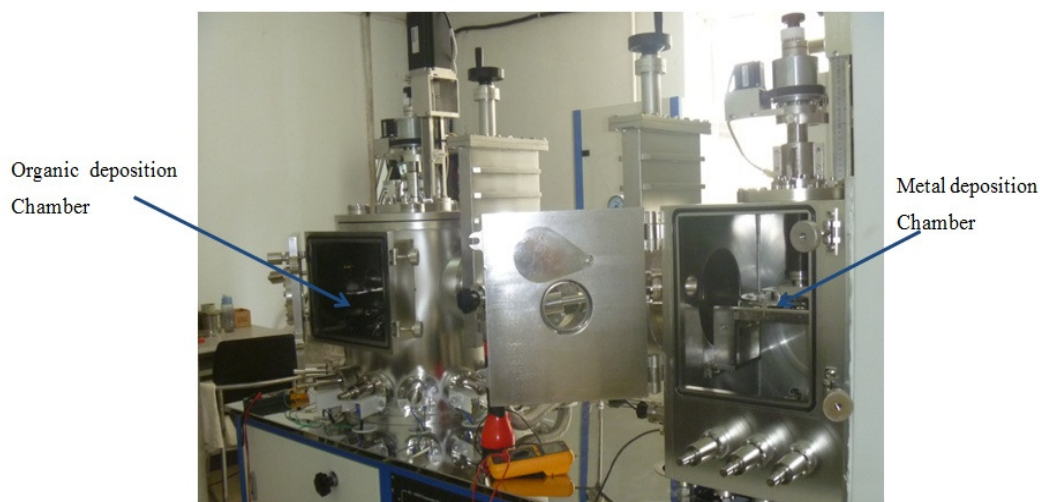


Figure 14: Picture of organic thermal evaporation system housed in ESRI.

After fabricating the LSCs, optical and electrical characterisation systems were used to measure key parameters, including were: the absorption, transmission and emission spectra, and the IV curves.

3.2.3- LSCs' Characterisation

3.2.3.1- Optical Characterisation

The photo luminescent spectra of the LSCs samples were all measured using a Perkin Elmer luminescence spectrometer LS50B.

A Cary Series UV-VIS-NIR spectrophotometer was used to measure transmission spectra. The absorption spectrum was calculated from the transmission spectrum, T, using the following expression [65]:

$$a = 2 - \log_{10} (T) \quad (6)$$

3.2.3.2- Electrical Characterisation

To characterise the electrical properties of the fabricated LSCs, a testing platform, consisting of a solar simulator (global air mass 1.5 (AM 1.5, 1000 W/m²)), a solar-cell frame and a precision semiconductor parameter analyser (Agilent 4156C), was set up. Measuring the IV curve of the solar cells was carried out by scanning an applied voltage across the solar cell and measuring the corresponding current. The conditions under which efficiency was measured were carefully controlled in order to generate accurate comparison between the performances of the various LSC devices. Thus, the parameters that were taken in consideration were the spectrum and the intensity of the incident sunlight, and also the temperature of the solar cells. Figure 15 shows a typical IV curves for a solar cell with illumination under 1 sun and without illumination.

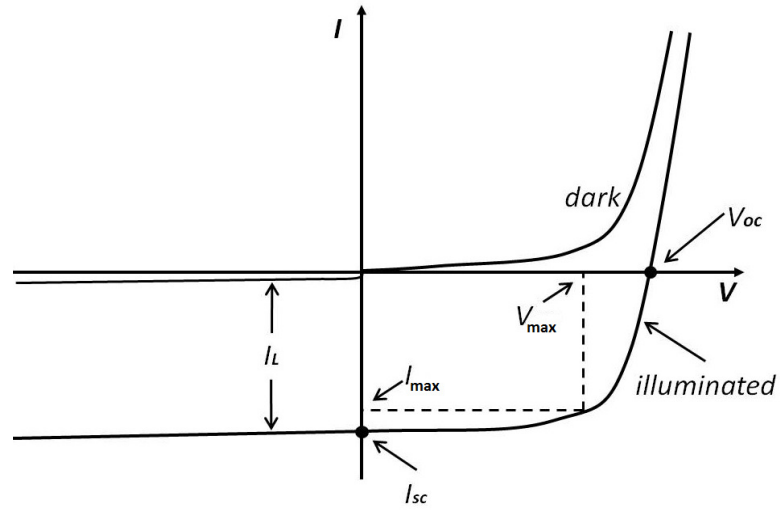


Figure 15: Typical IV curves for a solar cell with and without illumination, showing the cell short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) points, as well as the maximum power point (V_{max} , I_{max}) [66].

The key interesting parameters in Figure 15 are: the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}), which are the maximum current and voltage, respectively, which can be attained from a solar cell. Note that, at both of these operating points, the power from the solar cell is zero. The fill factor, "FF", is a parameter which, in conjunction with V_{oc} and I_{sc} , determines the maximum power that can be attained from a solar cell. The FF is the ratio between the maximum power (represented by the square in Figure 15) and the full rectangle spanned by the V_{oc} and I_{sc} values. A more commonly used expression for the FF can be determined as followed [67]:

$$FF = \frac{I_{max} V_{max}}{I_{sc} V_{oc}} \quad (7)$$

The primary parameter extracted from the IV curve is the PCE [68, 69], which describes the general efficiency of the solar cell. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. The formula for the PCE is:

$$PCE = \frac{I_{sc} V_{oc} FF}{P_{in}} \quad (8)$$

The IV curves of solar cells are important for the characterisation of the properties of LSCs. In all experiments, tests of the short-circuit current from PV cells are made to characterize properties of LSCs. The solar cell frame consists of four 20mm × 10mm polycrystalline silicon solar cells, of efficiency 12%, connected in-series, which were used to collect the light emerging from the four edges of the fabricated organic LSC. All the organic LSC samples made had a surface area 20mm× 20mm. The PCE of an LSC is given by [69]:

$$PCE_{LSC} = \frac{I_{sc} V_{oc} FF}{P_{in} * S_{LSC}} \quad (9)$$

where P_{in} is the input power (typically 1 kW/m² for a solar simulator) and S_{LSC} is the surface area of LSC, which is exposed to the incident light.

In summary, we have discussed the development of the LSC and also the approaches to improving their performance. The following chapters are based on three journal articles and an IEEE conference paper that were developed throughout this PhD project. The IEEE conference paper discusses the design and development of dielectric-metal thin film structures for use in applications requiring the control of thermal and solar radiation propagating through glass windows. Two of the journal articles focus on the encapsulation of high efficiency organic LSCs and transparent organic LSCs for BIPV applications, while the third journal article presents a new dual-dye region LSC structure capable of mitigating the reabsorption loss through proper selection and partitioning of the dye molecules in two regions.

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The following chapters are not included in this version of the thesis at the author's request.

Chapter 4

This chapter is an exact copy of the following refereed IEEE conference paper:

Yamna El Mouedden, Ramzy Alghamedi, Mohammad Nur E Alam, Mikhail, Vasiliev and Kamal Alameh, "Thin Film Coatings for Solar and Thermal Radiation Control Prepared by Physical Vapour Deposition", In *Proceedings, 9th International Symposium on High Capacity Optical Networks & Enabling Technologies (HONET-2012), Istanbul, Turkey, December 12-14, 2012*. doi:[10.1109/HONET.2012.6421440](https://doi.org/10.1109/HONET.2012.6421440)

Chapter 5

This chapter is an exact copy of the following journal article:

Yamna EL Mouedden, Baofu Ding, Qunliang Song, Guangji Li, Hoang Nguyen and Kamal Alameh , "A Cost-Effective, Long-Lifetime Efficient Organic Luminescent Solar Concentrator", *Journal of Applied Physics*, 118, 015502. (2015). doi:[10.1063/1.4923389](https://doi.org/10.1063/1.4923389)

Chapter 6

This chapter is an exact copy of the following journal article:

Yamna EL Mouedden, Baofu Ding, Qunliang Song, Guangji Li, Kamal Alameh, "Encapsulation of tandem organic luminescence solar concentrator with optically transparent triple layers of SiO₂/epoxy /SiO₂", *IEEE Journal of Selected Topics in Quantum Electronics (JSTQE)*, Special Issue on Organic Nanophotonics, 22(1), NO. 1, January/February 2016. doi:[10.1109/JSTQE.2015.2444593](https://doi.org/10.1109/JSTQE.2015.2444593)

Chapter 7

This chapter is being prepared for publication:

Yamna EL Mouedden, Baofu Ding¹, Qunliang Song, and Kamal Alameh "Dye Region Partitioning for Reabsorption Loss Mitigation in Luminescent Solar Concentrators"

CHAPTER 8

8- CONCLUSION AND FUTURE WORK

8.1- CONCLUSION

8.1.1- Thin Film Coating development

The first work developed in Chapter 4 has been the optimisation of a metal-dielectric structure for use in applications requiring the control of thermal and solar radiation propagated through glass windows. An E-Beam, thermal evaporator and an RF Magnetron sputtering system have been used to deposit the thin film layers. Experimental results have shown that the measured transmittance spectra for the developed structures are in agreement with simulation results. The metal-dielectric layer combination has been optimised, demonstrating a coated transparent glass panel capable of transmitting 84% of the visible light through and reflecting most of the UV, solar and thermal infrared radiations using a dual E-Beam/thermal evaporation system.

8.1.2- High-efficiency Opaque Organic LSC Development

In Chapter 5, which is based on a published journal article, the development of an organic LSC, based on incorporating a blend of organic-semiconductor hosts and organic dyes into an optically transparent UV epoxy-based lamination layer, has been discussed. Experimental results have shown that the developed organic LSC can attain a PCE as high as 5.3%. In addition, results have shown that the lifetime of the device can be as high as 1.0×10^5 hrs, making it cost effective and suitable for future BIPV applications.

8.1.3- Transparent Organic LSC Development

8.1.3.1- Encapsulated Organic LSC Development

In Chapter 6, which is based on another published journal article, has been presented a method for encapsulating an organic luminescence solar concentrator, employing three optically transparent layers, an encapsulating epoxy layer and two insulating SiO₂ layers that prevented the dye dissolving into the epoxy layer. Results have shown that by co-coating two organic materials, namely Alq₃ and DCJTb with a layer of 100 nm of SiO₂ for protection, on clean ultra-transparent glass, and using UV epoxy for encapsulation, an active organic layer is formed, which absorbs blue light and emits at longer wavelengths around the peak spectrum of 614 nm. In addition, results have shown that the encapsulated organic LSC exhibits an ultra-long lifetime of $\sim 3.0 \times 10^4$ hrs and 60% transparency when operated in ambient environments, which is approximately 5 times longer than that of conventional organic LSCs without encapsulation. The development of a transparent stable encapsulated tandem organic LSC is attractive for BIPV applications.

8.1.3.2- Mitigating Reabsorption Loss using Dual-dye-region LSCs

Finally, the key reabsorption issue in LSCs has been discussed in Chapter 7, and a new proof-of-concept LSC structure has been developed, based on partitioning the active region of the LSC into two areas, namely, an internal central square (ICS) area doped with red fluorescent dyes, and an external surrounding frame (SF) area doped with green fluorescent dyes. Experimental results have shown that by employing this novel LSC structure, both the red waveband as well as the green waveband can reach the LSC edges with less resulting in a 21% increase in PCE, in comparison with conventional LSCs. This new LSC structure paves the way for further reduction in reabsorption loss, and is attractive for future BIPV applications. The strategy proposed in this work also opens up a new way to reduce reabsorption loss in all other types of LSCs, such as inorganic-dye-doped LSCs and quantum-dot-based LSCs.

8.2- FUTURE WORK

There is the possibility of future work for further research exploration in the area of thin films coated where wavelength-selective mirrors can be used to reflect the escaped emitted light from the waveguide layer of an LSC. In general, about 25% of the luminescent radiations escape into directions that cannot be trapped inside the LSC's active region [1], and this reduces the efficiency of an organic LSC. In the last few years, several groups have researched approaches to minimising the light escaping the LSC, based on: (i) aligning the luminophores [2] and (ii) the application of wavelength-selective mirrors for light trapping [3-5].

Therefore, it would be useful to investigate the introduction of dielectric wavelength-selective mirrors, to be coated on the two sides of the LSC device and optimise their characteristics in order to maximise the conversion efficiency of the LSC, as illustrated in Figure 35. Understanding the relationship between the wavelength selective-mirror characteristics and the organic dye concentration, partitioning and region shapes will be useful for optimising the efficiency of the LSC. As shown in Figure 35(a), the spectrally-selective mirror receiving the incident light can be divided into two different selected-mirrors. Mirror 1 can be coated on top of the green region of the LSC, thus letting the blue light through but blocking the green light, and Mirror 2 can be coated on top of the red region, letting the incident blue and green light through but reflecting the red light. On the back side of the LSC sample, another mirror, similar to Mirror 1, can be coated to reflect the green and red emitted light. Figure 35(b) also shows the simulated reflection curves for Mirrors 1 and 2, as well as the absorption and emission spectra of DCJTb and C₆ (right).

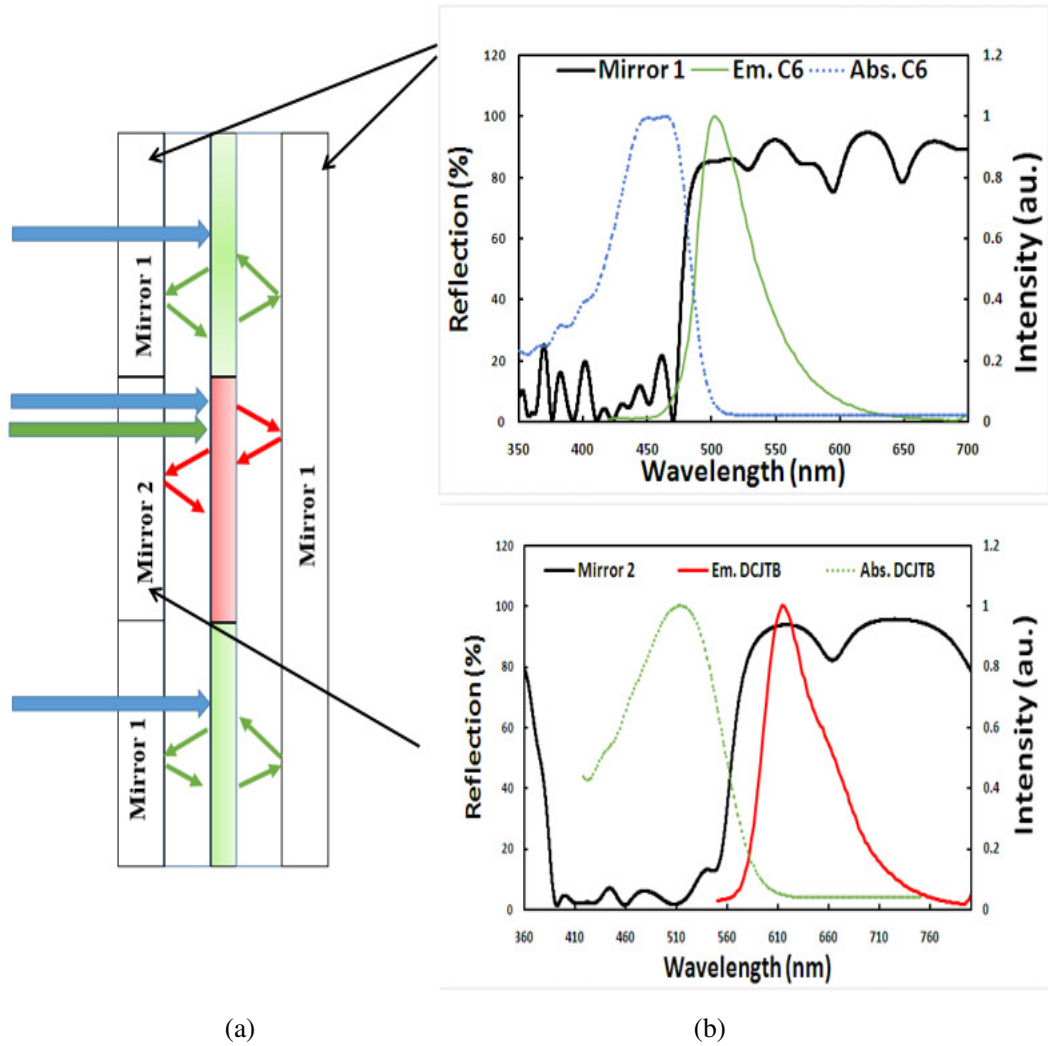


Figure 35: (a) Illustration of the partitioned LSC structure employing spectrally-selective mirrors for maximising the conversion efficiency, (b) the simulated reflection curves for Mirrors 1 and 2, as well as the absorption and emission spectra of DCJTb and C₆.

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