

Design, fabrication and preliminary testing of plasmonic luminescent solar concentrator devices

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Abstract. This paper details the design process, fabrication, optimisation and early-stage performance testing of Luminescent and Plasmonic Luminescent Solar Concentrator (LSC & PLSC) devices. A PLSC is a novel approach to solar concentrator technologies that utilizes the principles of luminescence and plasmonics to enhance the devices' solar energy conversion efficiency. This research analyses various mould dimensions, materials and lightguide fabrication methodologies to ensure equivalent LSC/PLSC devices were created in a reproducible method. The optimisation was an iterative process throughout the production and testing stages after which a $100 \times 100 \times 5$ mm PLSC was identified as the optimal for a rooftop installation. To ensure consistency in production as well as assessing the practicality of PLSC installations for building integration, performance testing has been conducted in both indoor and outdoor environments. Additionally, the lifespan of the devices are currently being investigated through ongoing performance evaluations. The incorporation of a reflective backplate has resulted in device efficiency improvements between 14–18% during indoor tests and was consequently included for all devices during outdoor performance analysis. Power conversion efficiencies of 2.3% and 1.7% have been recorded in sub-optimal conditions as well as concentration ratios of 11 and 9 for the PLSC and LSC devices respectively.

Keywords: Plasmonic luminescent solar concentrator / building integration (BIPV) / design / fabrication / performance testing

1 Introduction

The impacts of global warming and climate change are becoming increasingly evident as time goes on with flooding, droughts, and other extreme weather events occurring more frequently than ever before. A major contribution to these negative effects is the reliance on fossil fuel resources to meet global energy demands. Currently, fossil fuels account for 80% of the world's energy production, with the majority consisting of coal, oil, and gas [1]. This corresponded to an output of 36.6 billion tonnes of carbon dioxide (CO₂) entering the atmosphere in 2022 from fossil fuels and cement alone [2]. Greenhouse gas emissions worldwide are continuously increasing with CO₂ being the largest contributor, and if no action is taken, the consequences to the planet and its inhabitants will be catastrophic [3]. Because of this concerning trend, agreements such as the Climate Action Plan and the Paris Agreement have established objectives to reduce greenhouse

gas emissions and limit global temperature increases to within a 2°C increase through goals of being net-zero emission-wise by the year 2050 [4,5].

The built environment alone accounts for almost 40% of final energy use and energy process-related CO₂ emissions globally [6]. This necessitates the importance of reducing the CO₂ emissions from this industry, of which one possible solution is the deployment and integration of renewable energy in the built environment, both old and new.

The subject of this research is a novel type of solar concentrator technology, a Plasmonic Luminescent Solar Concentrator (PLSC) as a solar energy harvesting device for buildings. This device represents a novel approach to improve the Luminescent Solar Concentrator, first proposed in the 1970's [7]. The principle of operation for an LSC is quite simple in that the aim is to redirect and concentrate incoming solar radiation to the edges of the layer where the PV cells are situated. Figure 1 below demonstrates this process [8].

The polymeric lightguide, typically consisting of a transparent polymer mixed with a dye, enables a phenomenon known as total internal reflection (TIR) to

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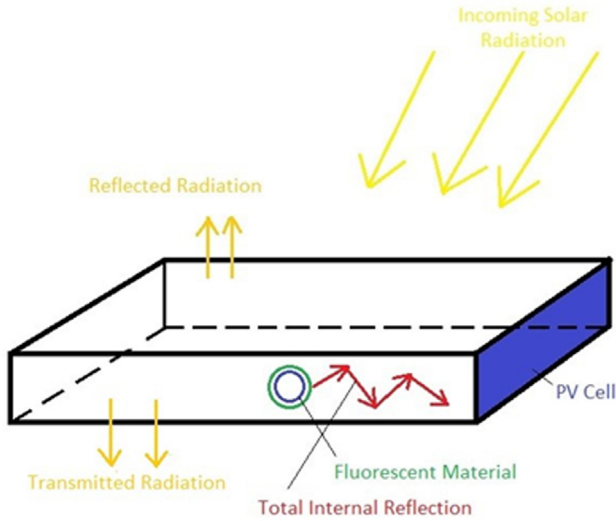


Fig. 1. Operating principles of a luminescent solar concentrator [10].

occur [9]. TIR takes place when light travels from a medium that has a higher refractive index to one with a lower refractive index at an angle that is greater than the critical angle, these mediums are often a polymer meeting an air boundary in an LSC/PLSC.

The polymeric lightguide is doped with a dye in order to introduce luminophores within the layer. The purpose of these luminophores is to absorb the incoming solar radiation and re-emit it at a longer wavelength, with the concept being to redirect the photons to the edges of the layer where the PV cells are positioned [9].

The optical efficiency of the LSC and PLSC devices can be calculated mathematically using equation (1);

$$\eta_{LSC} = \frac{\int \left[(1 - R(\lambda)) \left(1 - e^{-\alpha_c(\lambda)d} \right) \left(e^{-\alpha_{WG}(\lambda)L} \right) \right]}{\eta_{TR}(\lambda) j_{PL} (1 - \eta_{RA}(\lambda)) (1 - \eta_S(\lambda))} d\lambda, \quad (1)$$

where ' $R(\lambda)$ ' represents the lightguides reflectivity, ' $\alpha_c(\lambda)$ ' is the absorption coefficient of the luminophore, ' d ' denotes the thickness of the lightguide, ' $\alpha_{WG}(\lambda)$ ' is the absorption coefficient of the lightguide, ' L ' signifies the length of the lightguide, ' $\eta_{TR}(\lambda)$ ' is the maximum trapping efficiency, ' ϕ ' represents the quantum yield, ' $\eta_{RA}(\lambda)$ ' is the photon efficiency after reabsorption, and ' $\eta_S(\lambda)$ ' denotes the efficiency lost to reflection/scattering. It can be defined as the number of photons reaching the edges of the host material divided by the number of photons striking the surface.

Some advantages to this technology include:

- Customizable in terms of size and shape.
- The ability target specific wavelengths ranges of the solar spectrum.
- They do not need to track the sun to collect the direct and diffuse solar irradiation.
- Require less space than conventional PV installations, more suitable for urban environments.

- Low cost with minimal PV material required.
- No limitation on the solar concentration ratio.
- Efficient performance in both direct and diffuse lighting environments [11].

However, there are some drawbacks to this technology which require further research and development to overcome:

- Limited utilization of the Infrared and Ultraviolet spectra of light energy.
- Susceptible to temperature increases leading to reduced power conversion efficiencies.
- Optical and power conversion efficiencies decrease with increasing device size due to amplified energy loss processes in the lightguide.

A Plasmonic Luminescent Solar Concentrator (PLSC) takes this technology a step further and adds a plasmonic element to the lightguide. In this case, metal nanoparticles (MNPs), typically gold or silver are added to the polymer as well as the luminophore in order to further enhance the absorption and emission capabilities of the lightguide, with improvements ranging between 1.4–2.3 times a comparative bare PV cell [12–14]. Gold and Silver are often the metal nanoparticle of choice due to their relatively unique properties of having high refractive indices, surface plasmon resonance wavelength in the visible range, lower costs relative to other rare earth metals like europium or terbium [15,16], higher chemical stability, easy to fabricate with required sizes and shapes, and compatibility with polymers [17,18]. These properties make them excellent candidates for a phenomenon referred to as surface plasmon resonance (SPR).

Surface plasmon resonance refers to the collective oscillation of the conduction electrons whenever light interacts with a metal. This happens when light strikes a metal nanoparticle and the electromagnetic field attached to it is strong enough to exert a force on the conduction electrons displacing them from their natural orbital positions. This displacement induces an electrical dipole within the MNP with a force opposite to the electromagnetic field which pushes the electrons back towards their original position resulting in oscillations with a frequency known as the plasmon resonant frequency [19]. The oscillation frequency observed is dependent on the size, shape, and the electron density of the metal nanoparticles. The main benefit of this phenomenon for PLSC applications is that SPR greatly enhances the electric field near each MNP, which in turn means that the optical absorption and emission of each dye particle in the appropriate proximity to the MNP is also enhanced as there are more electrons in the locality for the particles to absorb. This form of device enhancement is heavily governed by the doping concentrations of both the dye and the MNPs. If the concentrations are too high, saturation can occur which induces a phenomenon known as quenching, where the luminophore and the MNP transfer the photons amongst themselves instead of emitting them and therefore reduces the maximum possible power conversion efficiency of the device. If the doping concentration is too low, the enhancement effect will simply not occur as there are not enough of either particle in proximity to absorb and

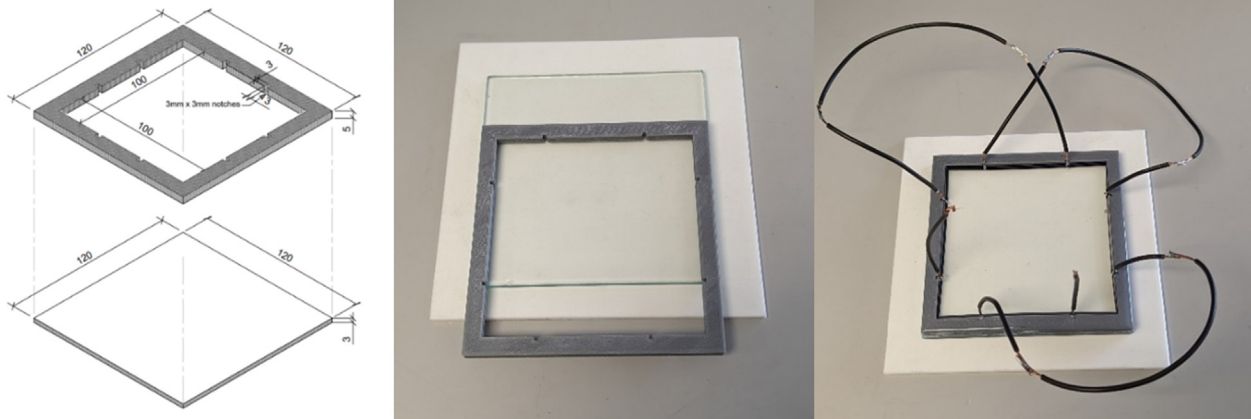


Fig. 2. (a) 3D Printed Mould Frame Schematic; (b) Mould Being Prepared; (c) Mould Prepared with PV Cells Connected Upright Within.

emit the incoming photons. This enhancement requires a fine balance between the concentrations of both doping agents.

This study focuses on the design, fabrication, and indoor & outdoor performance testing of various PLSC, LSC and reference cell devices. It aims to build on the work of previous research by scaling up the size of the devices and running performance analysis in both indoor and outdoor environments [14].

2 Methodology

The methodology section of this study is separated into three: design, fabrication, and performance testing.

2.1 Design

The design section of this study refers to the fabrication methodology of the layers and the size, shape, and materials of the moulds in which the PLSC & LSC layers were fabricated and allowed to polymerize. Initially, the idea was to produce layers in a frame, remove them, and attach the PV cells to the edges of the layers independently. However, this approach was deemed to be too difficult for any large-scale production purposes in a lab environment, and more suited to a manufacturing sector with suitable equipment.

As an alternative, new layer moulds were designed for casting and polymerizing the layers, as illustrated in Figure 2. In this design, a $120 \times 120 \times 3$ mm thick glass substrate was bonded to the mould frame. The mould frame was fabricated using acrylonitrile butadiene styrene (ABS) material via a 3D printer, which was selected due to its high thermal resistance. The frame had a 100×100 mm interior and a depth of 5 mm allowing for the attachment of 4 PV cells upright along the mould edges.

These dimensions were determined based on the extensive simulations of the devices performed previously [8]. The 3 mm cutouts in the design were incorporated to provide space for soldering wire connections to each PV cell

so that they can be connected in both series and parallel when being placed in the large outdoor panel in rows of 5 devices.

The PV cells used in this study were supplied by DMEGC Solar and were precisely cut to a size of $100 \text{ mm} \times 5 \text{ mm}$ size by SunWare GmbH to fit along the four inner faces of the mould. These PV cells have a rated solar efficiency is 22.0%, a Nominal Operating Cell Temperature (NOCT) of $42 \pm 3^\circ\text{C}$, and a Temperature Coefficient of P_{max} is $-0.330\%/^\circ\text{C}$. To prevent short circuiting the connections whilst connecting the PV cells together in series, only one busbar was soldered and wired on either side which led to a decrease in the maximum efficiency to 14%.

2.2 Fabrication

Mould fabrication required attaching the 3D printed frame design to the glass substrate. The remaining fabrication stages involved the LSC & PLSC layer production as well as the assembly of the large outdoor panel in which these devices were to be placed.

2.2.1 Layer Production

The polymer selected as the host material for the lightguide in this study was polydimethylsiloxane (PDMS), more specifically the 'SYLGARD 184 Silicone Elastomer' from Dow. Whilst previous work used polymethyl methacrylate (PMMA), the move to PDMS was made due to its comparably high transparency over the broad wavelength range, its increased biocompatibility, lower toxicity, and compatibility with the solvents and plasmonic materials required [20–25]. The fabrication methodology was developed through a combination of performing a literature review and various trials in the lab, it is as follows:

- Prepare a stock solution of Dichloromethane and the dye of choice. This study required a 70 ppm concentration of Lumogen F Red 305 dye). This was prepared by placing the required amount of dye into a beaker of known

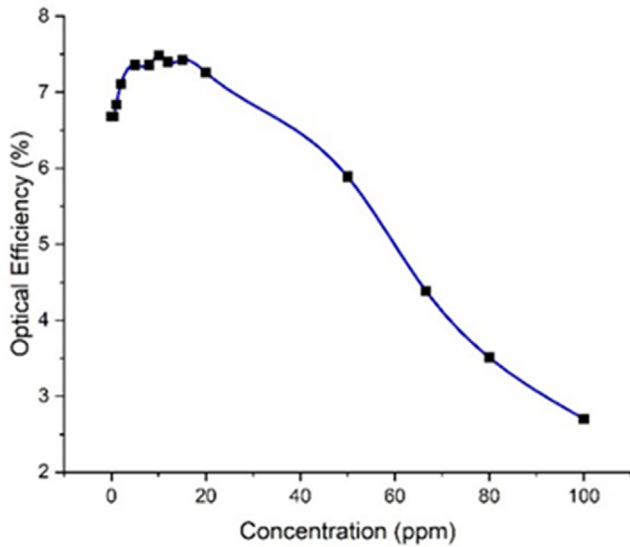


Fig. 3. Modeling results of the effect varying metal nanoparticle concentration has on optical efficiency.

dichloromethane quantity and mixing thoroughly using a magnetic stirrer at 300 rpm at 40 °C for 5 m. If producing PLSC layers, the quantum dots/metal nanoparticles should be included at this stage at the required concentration. In this study, gold core, silver shell nanorods at a concentration of 10ppm have been included after previous small-scale PLSC studies and extensive plasmonic modelling had been performed [10,14].

- The stock solution is placed into the polymer precursor in a separate beaker and allowed to stir at 40 °C at 300 rpm for 15 m.
- An equal quantity polymer catalyst is then manually stirred into the mixture briefly before being magnetically stirred at 200 rpm at 40 °C for 3 m as it quickly becomes viscous if left for too long.
- The solution is degassed to -0.5 Bar to remove trapped air. Any remaining bubbles can be manually removed from the surface using a sharp pipette tip.
- It is important to note that this entire procedure should be completed within 45 m as at that point the solution then begins to polymerise and can result in difficulties pouring/casting etc subsequently causing the fabrication of uneven layers.

The selection of the Lumogen F Red 305 dye was in part due to a literature review detailing the performance of other LSC devices as well as tests performed using a modelling software developed within the research group which determined that the red dye performs the best with comparisons made to other lumogen violet, yellow and orange available at the time [26–30]. A MNP concentration of 10 ppm has been selected following the modelling of various doping concentrations of gold-core silver-shell nanorods interacting with 70 ppm Lumogen F red dye in

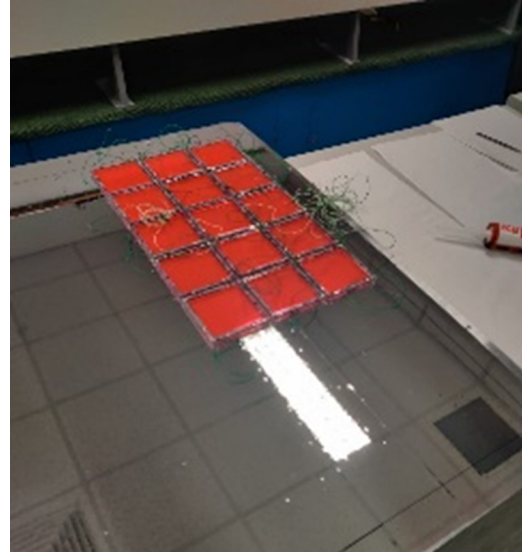


Fig. 4. Rows of LSC layers being attached to reflective backplate.

devices of dimension 100 mm × 100 mm × 5 mm, as shown below in Figure 3.

2.2.2 Panel Production

The production process for the outdoor panel involved initially sanding down the 1 m² aluminum backplate to prepare it for the attachment of a reflector. A DF2000MA reflective film from 3M with a measured reflectivity value of 0.98 was selected and attached at this stage. This helped ensure that the devices received the maximum amount of solar radiation possible. Afterwards, the devices were arranged in rows of 5 in the same class type with similar outputs. For example, 5 LSC layers with indoor measured outputs of ≈ 200 mW individually would be connected in series and a row of 5 of reference type devices would be connected underneath etc. This procedure is illustrated below in Figure 4. The backplate was then placed within a frame and positioned outdoors for testing purposes.

2.3 Performance Testing

Performance testing in this study is separated into indoor and outdoor sections.

2.3.1 Indoor

Indoor performance testing was performed using an Oriel Sol3ATM Class AAA solar simulator (Model 94603A) with a one sun output and a B2901A Precision Source/Measurement Unit (SMU – Keysight) as demonstrated in Figure 5. This testing was conducted to ensure the integrity of the PV cells remained after the polymerization of the lightguide, as it proved to be a delicate process and one in which cells could easily disconnect or even break.

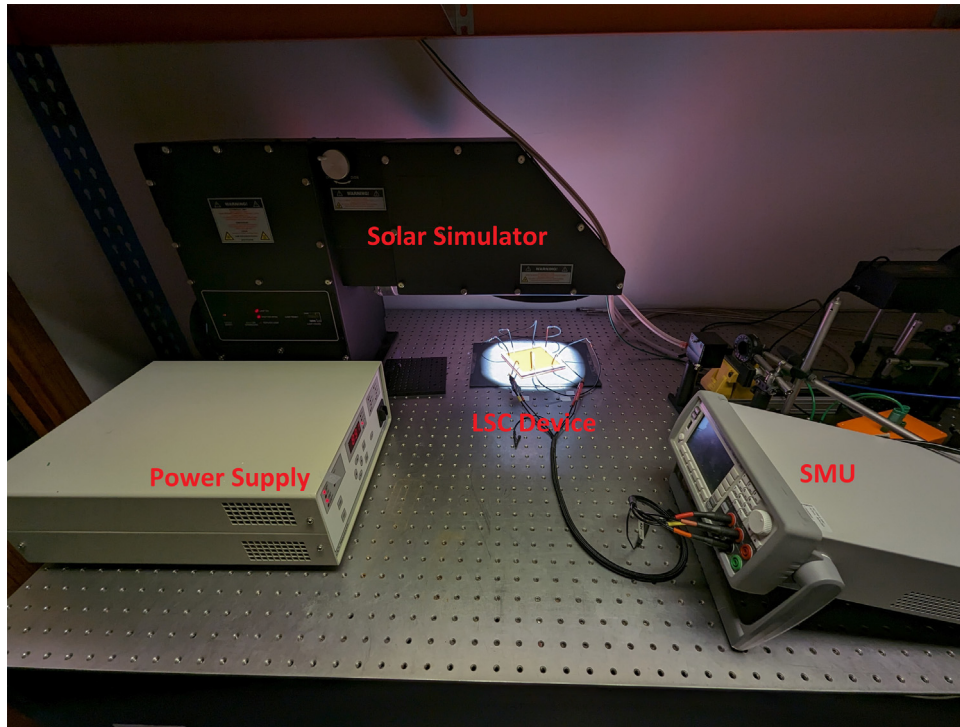


Fig. 5. Indoor testing setup.

Table 1. Power outputs from indoor testing on polarity A devices.

Sample name	Reflector	Maximum power (mW)
A1	Yes	200
A2	Yes	212
A3	Yes	184
A4	Yes	187
A5	Yes	189
A5	No	157
A6	Yes	185
A6	No	156
A7	Yes	190
A7	No	161

Table 2. Power outputs from indoor testing on polarity B devices.

Sample name	Reflector	Maximum power (mW)
B2	Yes	210
B2	No	180
B3	Yes	207
B3	No	182
B4	Yes	190
B4	No	160
B8	Yes	203
B8	No	175
B9	Yes	196
B9	No	163
B10	Yes	211
B10	No	180
B11	Yes	213
B11	No	180

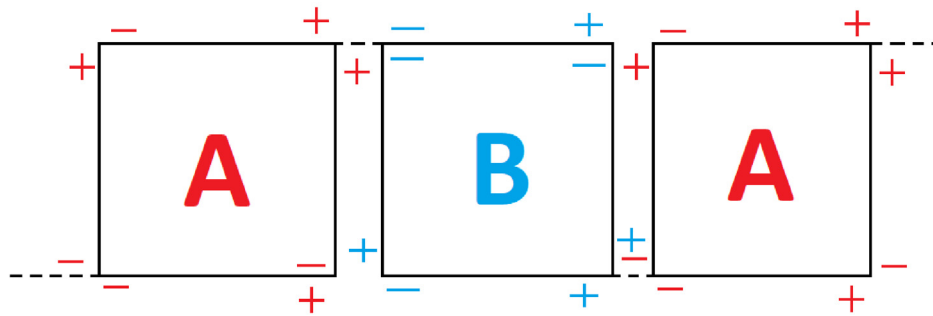
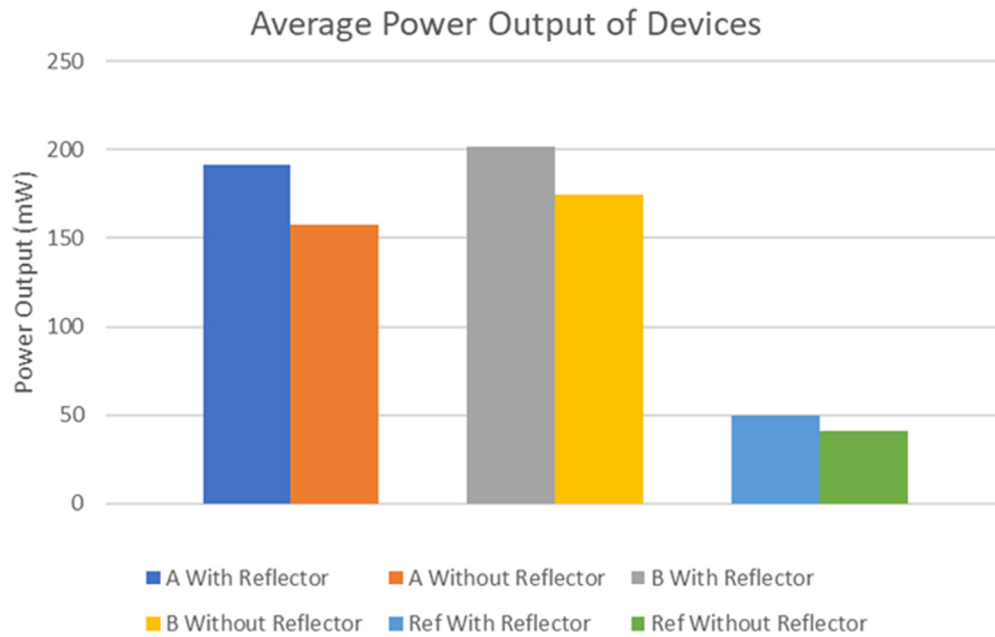
2.3.2 Outdoor

Unfortunately, due to health and safety concerns relating to getting the panel onto the roof, the outdoor results here are taken at ground level. The panel had to be situated just outside of the laboratory so that the connections could be met with a power supply meaning that the devices were placed in an area with a high pedestrian volume causing unpredictable shadowing on the devices. An attempt to overcome this involved conducting the measurements in the early morning, late evenings, and on weekends to record the maximum amount of unshaded data possible.

The outdoor measurements were taken using a Source Measurement Unit and an ISM 410 Solar Power Meter data logging pyranometer. This pyranometer is capable to detailing the type of solar radiation reaching the devices at any given time interval, i.e., direct, or diffuse.

Table 3. Power outputs from indoor testing on reference devices.

Sample name	Reflector	Maximum power (mW)
Ref. [1]	Yes	54
Ref. [1]	No	45
Ref. [2]	Yes	50
Ref. [2]	No	44
Ref. [3]	Yes	58
Ref. [3]	No	46
Ref. [4]	Yes	46
Ref. [5]	No	37
Ref. [5]	Yes	41
Ref. [5]	No	34

**Fig. 6.** Series & parallel connectivity of devices of the same type (A row of 5 LSC for example).**Fig. 7.** Average power outputs of the devices with a reflective backplate.

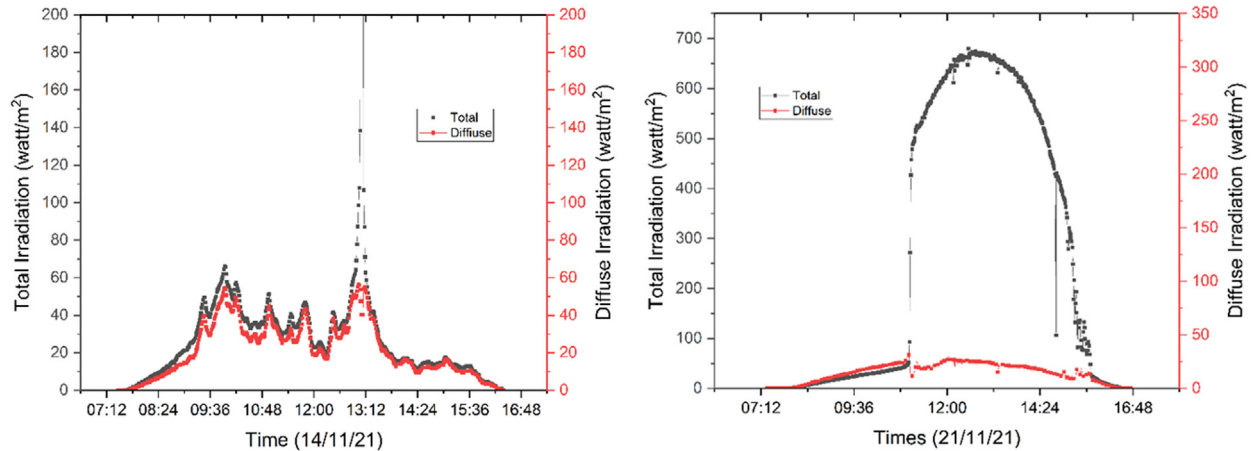


Fig. 8. Solar radiation of day of testing.

3 Results and discussion

Tables 1, 2 and 3 present the indoor performance results of various LSC and reference device outputs with and without the reflector.

The sample identifications A & B correspond to a labelling system used to indicate the electrical polarity of the devices. Within each device, the PV cells were arranged in such a way that positive and negative connections were soldered in series with two diagonally opposite corners having connectors in place to attach to the next device of the same type in parallel. Polarity A devices had a North-East positive connection whilst polarity B devices had a negative North-West connection. This arrangement is depicted in schematic format below in Figure 6. Reference devices refer to LSC layers fabricated in the same manner as all other LSC & PLSC devices but without the addition of any dye, therefore acting as a means to quantify the effects of the Lumogen Red 305 on the device performance. It should be noted that all devices above except for the reference type are LSCs, indoor testing on PLSC devices could not be completed due to delays in the procurement of supplies and deadlines for when outdoor results were required.

Figure 7 summarizes the enhancement to the power outputs of the devices that the inclusion of a reflective backplate introduced.

With an average power output overall for the LSC with a reflector being 198.4 mW and without a reflector being 169.4 mW, it is evident that the inclusion of the reflective backplate has proven to be beneficial. This represents an 14.61% increase in power output between the two configurations. The backplate also brought the average output for the reference devices from 41.2 mW without a reflector, to 49.8 mW with a reflector, an 17.27% increase in output. These results are in line with other studies identifying enhancements made with the inclusion of a reflector and an air gap to maintain the TIR effect where 10% and 12% improvements were observed using dielectric mirrors and narrow band reflectors respectively [31,32].

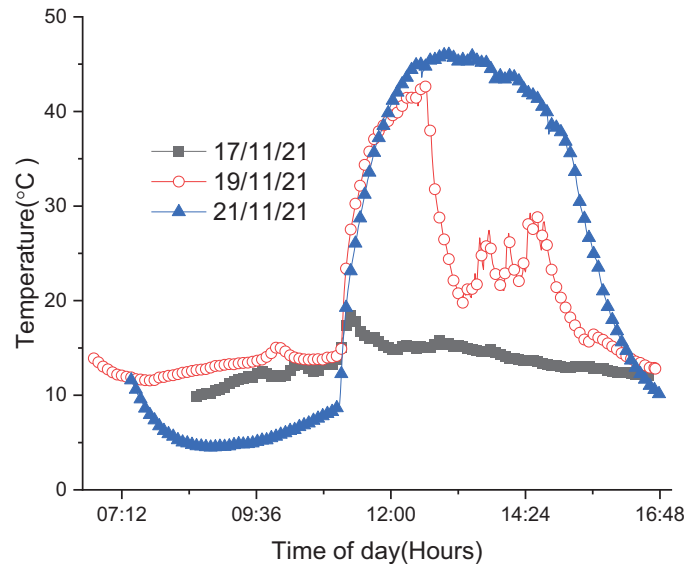


Fig. 9. Device temperatures over the duration of a days' testing.

Figures 8–11 present different data sets recorded from the outdoor test panel.

Figure 9 presents the temperature of the devices on the 17th, 19th and 21st of November 2021. The thermocouples were embedded within the devices, in contact with the PV cells on the mould side.

The power outputs of the devices have been recorded throughout a 5 °C–45 °C range of temperatures without any noticeable degradation or effects to the output.

Characterization of the devices was undertaken on November 21st in Dublin, Ireland when conditions were overcast and had high variability in cloud cover. The concentration ratios (the ratio of photons entering the device to photons reaching the edges where the PV cells are located) of the PLSC and LSC devices are included in Figure 10, and they demonstrate a consistent concentration ratio of 10 on average with the PLSC device outperforming the LSC throughout the entire period of testing.

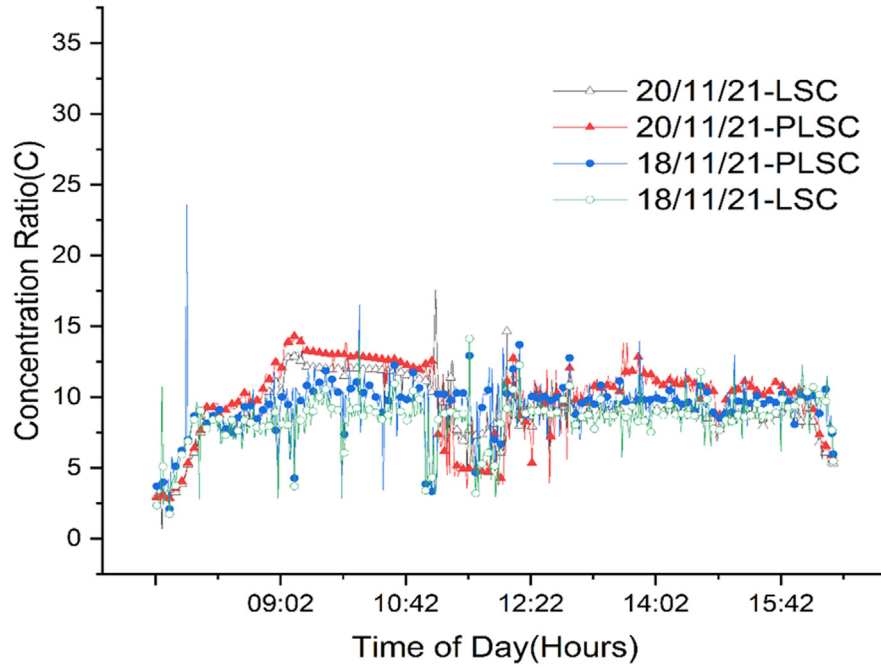


Fig. 10. Concentration ratio of the PLSC and LSC devices on two separate days.

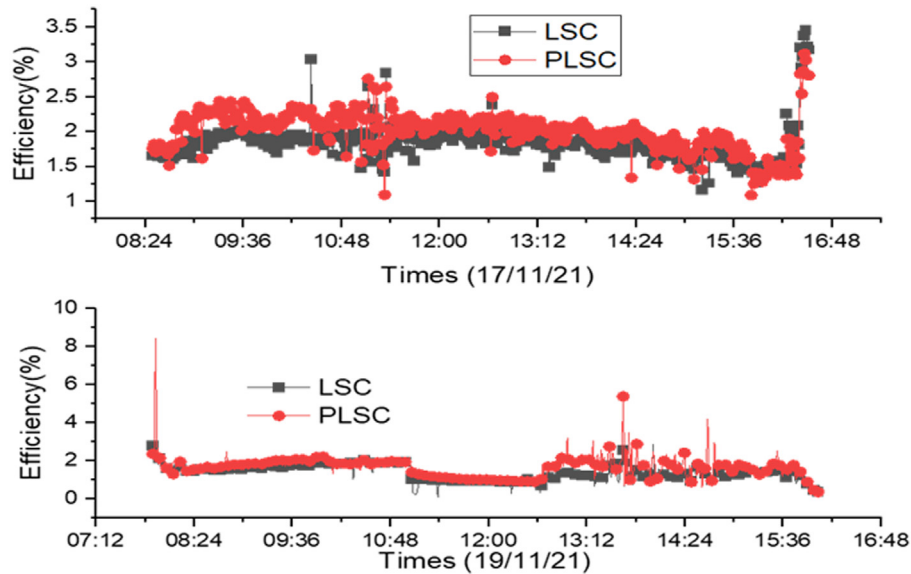


Fig. 11. Efficiency of PLSC & LSC device.

Figure 11 displays the power conversion efficiencies (PCE) of the PLSC & LSC devices on two separate occasions in mid-November. The PLSC has outperformed the LSC counterparts with an average PCE of 2.3% compared to 1.7% respectively and were calculated based on the lightguide area.

4 Conclusions

In conclusion, this study presents the design, fabrication, optimization, and performance testing of both larger scale LSC and PLSC devices in indoor and outdoor

environments. The aim of the study was to enhance the power conversion efficiency of the LSC through the inclusion of a plasmonic element.

The design aspect of the study focused on a novel approach to the fabrication of the (P)LSC devices in which the lightguides are cast to polymerize against the face of the PV cell which is pre-installed within the mould instead of the conventional approach where the PV cell is attached later. The methodology successfully produced 31 individual PLSC, LSC and reference devices proving that it is reproducible. The move to the PDMS polymer has been made for environmental reasons without any noticeable

tradeoff in performance. A device of dimension $100 \times 100 \times 5$ mm has been determined optimal when paired with a 70 ppm concentration of Lumogen F Red 305 dye and can be further enhanced with the incorporation of 10 ppm gold-core silver-shell nanorods.

The inclusion of a reflective backplate has proved to be beneficial, with power output enhancements of 14–18% observed during indoor performance analysis. Consequently, all outdoor devices were installed onto a panel which had a reflective backplate (reflectivity 0.98) included to maximize this benefit. Power conversion efficiencies of 2.3% and 1.7% as well as concentration ratios of 11 and 9 have been recorded for the PLSC and LSC devices respectively in quite un-optimized ground level outdoor conditions.

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