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Outdoor Characterization of a Plasmonic Luminescent Solar Concentrator

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Abstract: Plasmonic Luminescent Solar Concentrators (PLSCs) have been shown to enhance the optical performance and power conversion efficiency of LSCs, due to added plasmonic gain in the medium. Despite the promising outlook of a PLSC through plasmonic coupling, device characterization and performance has not been verified in the real outdoor conditions, with varying direct and diffuse solar irradiation. In this work, characterization of a PLSC device of dimensions 4.5×4.5×0.3 cm³ embedded with Lumogen Red305 dye and plasmonic gain medium of gold core silver shell nanocuboids was carried out in outdoor conditions of Dublin, Ireland. Optimized PLSC device power output at different solar insolation's was compared to a reference photovoltaic (PV) cell and an optimized Luminescent Solar Concentrator (LSC) device. The effect of the solar discs position, solar insolation, PV cell surface temperature, diurnal, and seasonal variation on the performance of the PLSC device is studied. The key observation was that PLSC average power conversion efficiency was 1.4 times more than the PV cell in cloudy and diffuse solar conditions. The PLSC device performed 45% better than a PV cell in December than July, as December has higher diffuse solar irradiation. Even though the PLSC device absorbs only 31% and transmits 69% incident solar irradiation in the concerned visible range of 380-750 nm. The preliminary outdoor characterization on a small scale PLSC establishes its viability in a diffuse to direct solar radiation ratio throughout the year as well as establishing its benefits for integration in buildings.

Keywords: Plasmonic, gold core silver shell nanocuboids, luminescent solar concentrator, direct and diffuse solar irradiation, photovoltaic

Introduction

Luminescent Solar Concentrators (LSCs) were proposed in the late 1970s to generate low-cost solar electricity using an inexpensive static solar collector and intended for use in the built environment [1-4]. In its basic design, it is a transparent polymer waveguide, either homogeneously doped or coated with luminescent materials (dye, quantum dot, rare-earth). The luminescent material absorbs incident light and re-emits it at longer wavelengths and, in all directions, the portion of re-emitted emission that falls in the critical angle range of the waveguide is trapped and guided to the edges by total internal reflection (TIR), where it is collected by an optically coupled PV cell to generate electricity. The light concentration represented by solar concentration (photon concentration) ratio, represents the system's ability to concentrate solar energy, which defined as:

$$C_p = C_{geo} \times \eta_{opt}$$

Where the C_{geo} geometric concentration, the ratio of incident light collection area to edges area where the PV cells attached to collect concentrated light. η_{opt} , is optical efficiency, ratio of the concentrated photons to input photons energy in the wavelength range of interest.

LSCs have technological advantage: i) solar concentration ratio not limited by acceptance angle hence it can collect both the direct and diffuse solar irradiation efficiently; ii) static nature thereby no need for an expensive tracking system, this reduces the complexity and cost of the system, and it is easy to install and integrate in buildings; iii) emission of the luminescent material can be tuned with band gap of photovoltaic cell thus reducing

energy dissipation as heat and minimize the thermalization losses; iv) can be placed next to each other without the risk of shadowing their neighbors from the sun; v) Its color and transparency can be easily customized for aesthetical reasons, hence, can be employed in façades, building envelopes, and windows of buildings [5-6]. These factors make them favorable for BIPV design, as well as retrofitting the conventional buildings with LSC, either through PV power or through daylighting [7]. vi) the fabrication is compatible with low-cost manufacturing such as moulding and casting.

Despite having these advantages, LSCs are not yet commercially viable as the optical efficiency (OE) and power conversion efficiency (PCE) remains too low to make them cost-effective technology [8-12]. Energy loss mechanisms in LSCs are limiting the efficiency and are categorized into material and energy transportation losses. OE is highly dependent on the energy loss mechanisms associated with non-unity of fluorescence quantum yield of used luminescent materials, host polymer attenuation, escape cone, scattering, re-absorption, optical pathlength traveling emission [4, 13–16].

Since, its first inception in late 70s, researchers have been working on various aspects to improve the efficiency for example, use of different types of luminescent materials such as dye, quantum dot, and rare-earth materials [9, 17-23], combining multiple luminescent materials [24] geometric design [25-27], tandem structures [28], inclusion of diffuse reflectors [8,29], use of various PV technologies (p-Si, a-Si, mc-Si,c-Si,GaAs), adding photonic structures[29-30], aligning the luminescent species [31], thin-film LSC [32], development of raytracing and thermodynamic modelling to efficiently optimized the LSC device design and parameters to maximize the efficiency [33–35].

Recently, an alternative technology of plasmonic luminescent solar concentrator (PLSC) was proposed to improve OE and PCE [36–39]. To mitigate these energy loss processes in the LSC a gain medium of metal nanoparticles was included in the LSC. Plasmonic interaction can create a gain medium by enhancing the optical properties of luminescent species in the LSC that can compensate for energy loss processes and improve the optical performance. In a PLSC, metal nanoparticles (MNPs) are embedded in the host matrix along with the luminescent species. MNPs exhibit plasmonic optical properties and act as nano lenses i.e., they can localize incident electromagnetic radiation in subwavelength range through excitation of localized surface plasmon resonance [40], [41]. The localization of electromagnetic radiation enhances electric field intensity [42]. This behavior is exploited in the modulation of optical properties of luminescent species through plasmonic interaction in PLSC. In plasmonic interaction, when a luminescent species is placed in the locally enhanced electric field, its excitation and absorption rates are modified [43,44] as well as, the quantum yield, non-radiative and radiative relaxation rates [45–47]. This plasmonic interaction is controlled by several parameters such as the spacing between the MNP and the luminescent species, spectral overlap of MNPs extinction spectra with the absorption and emission spectra of the luminescent species. The plasmonic interaction parameters have been optimized for different PLSC device designs and different MNP fluorophore combinations [36,37, 48, [49]. 25.8 % [48] and 30% [37] increase in the edge efficiency was reported on indoor testing of a thin film PLSC and a homogeneous PLSC respectively. This study has undertaken a detailed outdoor characterization of PLSC devices to understand the in-depth functionality of PLSC devices and to gain an insight into the role of plasmonic interaction under different solar insolation.

Despite the promising nature of a PLSC, there is limited research in validating PLSC device functionality in real outdoor conditions. A PLSC, like an LSC should showcase improved functionality in diffuse solar radiation. The

average annual ratio of diffuse to direct normal irradiation is 50%-55% for northern European countries [50]. This ratio is higher (over 65%) during the winter months. Thus, studying the PLSC device in outdoor conditions can help to determine its feasibility. In this research, characterization of an optimized PLSC device of dimensions $4.5 \times 4.5 \times 0.3 \text{ cm}^3$ was analyzed in Dublin, Ireland under various solar irradiation conditions. Real time simultaneous measurement of the power output from the PLSC, LSC, a blank host matrix and a reference PV cell was undertaken. The measurements allow the characterization of the PLSC device with reference to a PV cell and LSC device and the dependence of the electrical parameters on temperature, light intensity and solar disk position was studied.

Methods

LSC/PLSC waveguides were fabricated using Silicone encapsulant polymer (DOWSIL Optical Encapsulant) as the host matrix and were cured in an oven at 50°C . Lumogen Red305 dye (BASF Chemical) and gold core silver shell nanocuboids were embedded in the host matrix of the PLSC device. The optimized doping concentration of the dye and the nanocuboids in the PLSC device was 70 ppm and 1.1 ppm, respectively. The PLSC was optimized by varying the doping concentration of the nanocuboids in the waveguide and studying the emission from the edge of the PLSC waveguide, reported in earlier work [37]. 1.1 ppm nanocuboid doping concentration led to the maximum fluorescent enhancement from the edge of the PLSC. For the LSC device, the host matrix was embedded with 70 ppm Lumogen Red305 dye. $50 \times 3 \text{ mm}$ c-Si solar cells were attached to one edge of the waveguide using an optically transparent conductive adhesive with an acrylic resin base and the connecting wires were soldered to the PV cell for electrical characterization. The PV cell had an efficiency of 19% under standard test conditions with a maximum power output of 28.5 mW under AM 1.5G 1000 W/m^2 . A blank Silicone polymer waveguide and a bare PV cell were used as a reference. An electrical setup was designed to conduct simultaneous measurement of multiple devices in outdoor conditions. The circuit diagram can be seen in Fig. 1.

Fig. 1 Circuit diagram of the outdoor setup to measure the current, voltage and temperature from different devices.

A load resistor value was selected based on the maximum power output from the PLSC device in indoor testing under STC. To avoid a high current a shunt resistor with a conversion factor of 2 A-200 mV was connected in series circuit. The current was measured through the shunt resistor and the voltage was measured across the device. A K-type thermocouple was used to measure the temperature of PV cells and LSC/PLSC waveguides. The solar irradiance was measured using a Kipp and Zonen CMP6 pyranometer.

The pyranometer had a spectral range of 285 nm to 2800 nm and a response time of 18 s. Data from the PV cells, shunts, thermocouples were acquired by a data logger (Agilent 3472A LXI). The data logger recorded the voltage, current and temperature data at 60s interval. The setup was mounted horizontally on the roof of the Simon Perry Building, Dept of Civil, Structural and Environmental Engineering at Trinity College Dublin as seen in Fig. 2.

Fig. 2 Photograph of the roof with focus on the main components and their relative position such as pyranometers, data logger and the device box. The solar device and pyranometers were placed in horizontal plane (horizontal surface)

The outdoor setup was covered by a 4 mm thick low iron glass (Pilkington Optiwhite) as shown in Fig. 3. The low iron content in the glass maximized the solar energy transmittance (92%). Data was collected from 30th June to 1st August in 2019 under different weather conditions. This data was used to extrapolate the performance of the devices for the month of December.

Fig. 3 Photograph of the outdoor setup consisting of PLSC and LSC devices.

Results and Discussion

The electrical power output data from a clear sunny day and a cloudy day with varying cloud cover is compared. Measured solar irradiance on a sunny day (3rd July 2019) rated as 1 okta and a cloudy day (30th June, 2019) with considerable variation in the cloud cover from 3 to 6 oktas can be seen in Fig. 4a, b. Sunrise at this location is at 5:00 and sunset is at 21:56. As can be seen from Fig. 4a, a drop in solar irradiance is observed from 10:00 to 11:00 on 3rd July, this is due to a cloud passing over the solar disk. The electrical power output from the devices and the references can be seen in Fig. 4c, d. It is observed that the PLSC device performs on average approximately 1.2 times better than the LSC device in both sunny and cloudy conditions. On a sunny day when

the direct to diffuse radiation ratio is high, the bare PV cell performs better than the PLSC device from 11:00 to 14:00, the PLSC device performance overtakes the bare PV cell when the solar disk is closer to the horizon at morning and evening hours. This shows a dependence of the power output on the position of the sun and the angle of incidence. For a cloudy day, the PLSC device outperforms the bare PV cell throughout the day. For the same radiation intensity when a cloud covers the solar disk the fraction of diffuse light increases significantly, the spectral distribution of diffuse light is different from direct light. Short-wavelength light is scattered more efficiently because of the cloud cover. Therefore, the portion of short wavelength in the overall irradiation is higher [51]. Lumogen Red305 dye used in the PLSC device have higher absorbance coefficient in short wavelength from 350 nm to 550 nm. Similarly, the gold core silver shell nanocuboids' plasmonic properties are also dominant in this wavelength range. These factors together contribute to improving the optical performance and result in higher power output of the PLSC device than the bare PV cell on a cloudy day. In absolute terms, the power output will be higher on a sunny day as compared to a cloudy day because of a higher number of incident photons. Since, the test is carried out for a horizontally placed device but for building integration applications, PLSC would be most likely integrated in the façade and/or windows, which are vertical or inclined, thus, mostly receiving diffuse irradiation.

Fig. 4 Solar irradiance from sunrise to sunset on a) 3rd July 2019 when average cloud cover was 1 oktas and b) on 30th June 2019 when the average cloud cover was 6 oktas. Average edge power output from the PLSC, LSC devices and the references on c) 3rd July 2019 and d) 30th June 2019.

As mentioned, the PLSC device performs better than the LSC, and bare PV cell during the morning and

evening hours. In Fig. 5 the day has been divided into three regions morning, afternoon and evening based on the sun's altitude. Throughout the day the sun changes its position in the sky, at sunrise and sunset the altitude is zero degrees. The sun's daily maximum altitude is called solar noon and does not typically coincide with clock noon. On 3rd July 2019 the solar noon is at 13:28 at an altitude of 60°. Morning has been considered the time when the sun's altitude increases from 0 to 30 degrees. The afternoon is when the sun's altitude changes from 30 to 60 degrees and then back to 30 degrees. The evening duration is similar to the morning when the sun's altitude changes from 30 to 0 degrees at sunset.

A continuous change in the ratio of efficiency of PLSC device to the PV cell is seen on the sunny day. The ratio of efficiency is higher (orange region) when the sun's altitude is lower than 30 degrees for both morning and evening as compared to afternoon (yellow region). The drop in the ratio of efficiency in the morning of 3rd July 2019 can be attributed to the passage of clouds at that time. Diffuse radiation comes from all the angles while direct follows the path of the solar disc. When the solar disk is closer to the horizon, the sun rays travel a longer distance to reach the device thus getting more scattered and diffuse as compared to when the sun is at the zenith. The diffuse radiation gets absorbed by the PLSC device and therefore leads to the enhanced power conversion efficiency. For countries lying at high latitudes such as northern European countries the solar disk will be closer to the horizon for a longer duration than the countries near the equator. These results show the feasibility of the PLSC device in such countries.

Fig.5 Ratio of power conversion efficiency of PLSC device to the bare PV cell on 3rd July 2019 (clear day). The time has been divided into three regions based on the sun's altitude in the sky.

The normalized power conversion efficiency of the PLSC device and the bare PV cell with the radiation intensity on both the days is shown in Fig. 6a, b. The efficiency of solar cells decreases with a decrease in the radiation intensity. However, it is observed in Fig. 6a that the slope of the PLSC efficiency trend is lower than the slope of the PV efficiency trend. This higher efficiency of PLSC device in low light intensity is explained by its performance improvement in morning and evening time of the day. These results also show that the PLSC waveguide will be less susceptible to spikes in the solar radiation intensity as compared to traditional PV cell. This can prove advantageous for large scale installations as it can reduce the strain on the grid.

Fig. 6 Normalized power conversion efficiency variation of PLSC device and bare PV cell on a) sunny day 3rd July 2019 and b) cloudy day 30th June 2019.

PV cell performance is negatively impacted when their temperature rises. The bare PV cell reaches the temperature of 65°C during noon of the sunny day. The temperature variation of the bare PV cell and the PV attached to the PLSC waveguide throughout the clear day can be seen in Fig. 7a. It was observed that above 300 W/m² PV cells attached to the PLSC waveguide had a temperature lower than the bare PV cell. The maximum temperature difference between the PV cell attached to the PLSC waveguide and bare PV cell is 7°C and 11°C on the cloudy day and sunny day respectively. This 11°C can translate into the c-Si PV cell working more efficiently when attached to a PLSC waveguide. It should be noted that the ambient temperature was 18°C at peak position of the sun.

The impact of the PV temperature on the PLSC device efficiency and bare PV cell efficiency can be seen in Fig. 7b. The bare PV cell's efficiency starts decreasing in the afternoon after the cell reaches the temperature of 65°C. However, the PV cell attached to the PLSC waveguide runs cooler and shows a more gradual decrease in efficiency in the afternoon.

Fig. 7 a) Temperature variation of bare PV cell and PV cell attached to PLSC waveguide on a clear sunny day, b) Variation of the normalized efficiency of bare PV cell and the PLSC device throughout the day.

In the PLSC waveguide, the light collected in the short wavelength range is downshifted to longer wavelengths by the embedded lumogen dye before reaching the PV cell, thus less energy is available to heat up

the cell. The thermal conductivity of Silicone is 0.2 W/m-K, so even though the waveguide warms that heat is not readily transferred to the edge of the waveguide. For the bare PV cell, the heating is mainly caused by the absorption the incident light even if most of it not used for charge pair generation.

On a clear summer day, the PV cell outperforms the PLSC device, however, on a cloudy summer day the PLSC device has a higher power output than a PV cell as previously shown in Fig. 4d. The higher performance of PLSC device can be attributed to higher percentage of diffuse radiation on a cloudy day. It is important to see how the performance differs in summer and winter months as the amount of diffuse radiation is higher during winter months in Ireland. The data collected for the whole month of July was used to plot the average hourly power output from the PV cell and PLSC device. December corresponds to the month with the lowest irradiance sum, the average hourly spectral irradiance data for December is taken from (SolarEuropa PVGIS) [50]. It is observed that the highest average solar irradiance (476 W/m^2 and 127.95 W/m^2) is around noon for July and December as shown in Fig. 8a, b, respectively. For both the months the shape of the output power curve of the PLSC device closely follows the variation in spectral irradiance, as can be seen from Fig. 8c, d. This is similar to the observation for single days

Fig. 8 a), c) Daily average of solar irradiance for the months of July and December, respectively. b), d) Average power output of the PV cell and PLSC device for July and December, respectively.

The power output of the PLSC device is higher than the PV cell in December, on an average the PLSC gives 1.6 times higher power output than the PV cell in December. As compared to July, the PLSC device performs 45% better than the PV cell in December.

This shows the feasibility of PLSC device in winter months. Spectral data on an hourly basis for both the months was used to determine the monthly energy yield. The monthly energy yield of the PLSC device is calculated to

be 10.80 kWh/m² and 1.37 kWh/m² for July and December, respectively. Even though, the optimized PLSC absorbed only absorbed 31% and transmit 69% in the visible range of 380-750 nm, as demonstrated in the Fig.9.

Fig. 9 The transmission of PLSC and extinction spectra of used gold core silver shell nanocuboids metal nanoparticle.

The transmitted light can be used to control daylight and visual comfort in the built environment, therefore, the PLSC is multifunctional. Despite the higher energy yield of state-of-the-art silicon solar cell over a horizontally placed PLSC device. However, for those vertically placed, the PLSC is more efficient, that is evident from diffuse irradiation characterization. Therefore, the PLSC device can be a good alternative over a conventional PV in a BIPV setting.

Conclusion

The key observation from this work is that the PLSC device performed better than the bare PV cell in cloudy and diffuse light conditions. Power conversion efficiency of the PLSC device almost doubled under such conditions. One of possible reasons for this is enhanced plasmonic interaction in diffuse solar irradiation conditions. In diffuse solar irradiation, the blue light ratio is higher in the solar spectrum, and in that range the PLSC device has higher absorption and the plasmonic interaction dominates in this range of 300-575 nm. For both clear and cloudy days, the PLSC performed better than the PV cell during morning and evening. The relative increase in the performance of the PLSC device in morning and evening when the sun is closer to the horizon can be attributed to the high incident angle of the incoming diffuse solar radiation that is trapped in the waveguide. The average power conversion efficiency of PLSC device is 1.4 times the efficiency of the bare PV cell on a cloudy day. On a sunny evening when there were no clouds the PLSC device average's power conversion efficiency is 2.7 times the average efficiency of the PV cell. Thus, the PLSC device can be feasible in higher latitude countries where the sun is closer to the horizon for a longer duration. PV cell attached to the PLSC waveguide was 11°C cooler than the bare PV cell. Performance of the PLSC device with variation in solar radiation intensity was studied and it was observed that the PLSC was less adversely affected in low light as compared to PLSC. The PLSC device performed 45% better than a PV cell in winter month as compared to a summer month. The PLSC device might show promise as an integration into the facade of a building.

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Data Availability All the references cited are available.

Declarations Conflict of Interest The authors declare that they have no conflict of interest

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