Luminescent Solar Concentrator (LSC) windows for sustainable electricity generation over agricultural land

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ABSTRACT

Luminescent Solar Concentrators (LSCs) consisting of a transparent plate embedded with a high quantum yield luminescent dye may be used in conjunction with Photovoltaic (PV) cells to enhance the power output of the cells, thus lowering the cost per watt of the solar energy produced. The innovative front-facing LSC design was constructed and parameters tested include thickness of the acrylic waveguide, attachment methods of the LSC and PV cells, edge effect, layout, LSC enhancement per area and cell size. One specific application is incorporation into greenhouses, for which they are an ideal candidate to simultaneously harvest solar energy while enhancing the growth of plants inside, as well as reduce the heating effect in the greenhouse and evaporation. The dye in the LSC has been optimized for absorbing wavelengths of sunlight not useful for plant growth, and emitting at longer wavelengths closer to red which simultaneously improves photosynthesis and Si PV efficiency.

Keywords: luminescent solar concentrator, Lumogen Red 305, building integrated photovoltaic, front-facing photovoltaic

1 INTRODUCTION

While LSCs have been around since the late 1970's, more recent development in the efficiency and stability of dyes has sparked new interest in the field.[1,2] Incorporating LSCs into buildings have a couple advantages over traditional solar panels. The addition of a low-cost luminescent material surrounding the PV cell concentrates light onto the cell and significantly increases the power generated. The windows may then be used as Building Incorporated Photovoltaics (BIPV) which is another factor that reduces the cost per Watt of the system.

LSCs are composed of a high quantum yield dye or other luminescent material embedded into a flat polymer matrix waveguide. The LSC material is used to surround a photovoltaic (PV) cell that is optically-coupled to the waveguide material. When light is absorbed by the luminescent material, it is then re-emitted isotropically. A fraction of the emitted light, that which is equal to or greater than the critical angle of the waveguide material, is trapped in the matrix and wave-guided to the PV cell to be collected. See **Fig. 1**. This effectively concentrates light from a larger surface onto a smaller PV area increasing the power output of the cell. Traditionally, the PV cell is mounted on the edge of the waveguide (**Fig. 1** (**I**)) which leads to a high concentration factor, but low overall efficiency due to both self-absorption and low solar absorption. We have instead built a front facing design[3] with the PV cells surrounded by luminescent material, absorbing both direct sunlight and wave-guided concentrated light, as shown in **Fig. 1** (**II**). This layout allows for the PV cells to directly convert the solar irradiance to power, resulting in greater gain, and also reduces the distance photons have to travel in the waveguide. In addition, the LSC is separated into a thin luminescent absorbing layer and a thick waveguide layer, thereby allowing photons to travel a longer distance in the panel without re-absorption.

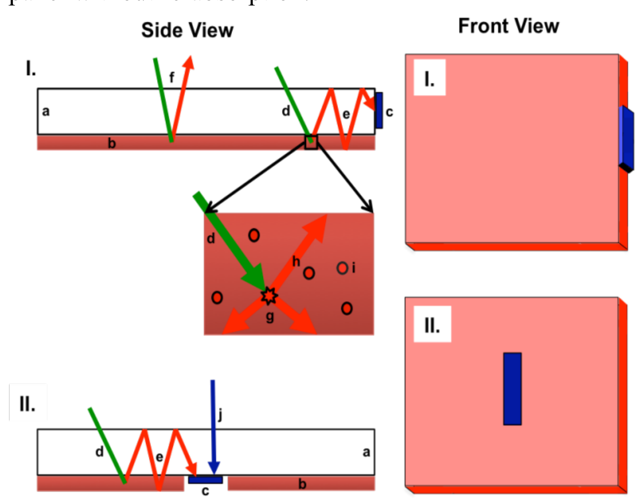

Figure 1: Schematic of conventional LSC design with side-mounted PV cells (**I**) with a magnified view of dye molecules embedded in the flexible acrylic sheet (**inset**); innovative LSC design with front-facing PV cells (**II**). **a**: acrylic panel; **b**: luminescent sheet; **c**: PV cell; **d**: incident photon absorbed by luminescent dye; **e**: photon emitted by luminescent dye, wave-guided and absorbed by PV cell; **f**: incident photon absorbed by luminescent dye and re-emitted at angle within escape cone; **g**: dye molecule excited by photon, light is downshifted and re-emitted

isotropically; **h**: downshifted photon is re-emitted into the waveguide; **i**: dye molecule; **j**: direct sunlight absorbed by front-facing PV cell.

In order to quantify the enhancement of the power generation of the PV cell due to the LSC, a performance parameter, termed gain, is defined. It is the power output of the LSC panel divided by that of an equivalent control cell, in terms of area and PV characteristics, but without luminescent material.

Gain = Power (LSC window) / Power (control cell)

These electricity-generating panels can be installed directly into greenhouses without requiring any additional structural costs. They could hence convert a greenhouse to generate all of the electricity that it uses with a relatively low payback time compared to traditional solar energy. In the first stage of this work, data was gathered in order to design an optimized LSC window. The second stage of this project was construction of an LSC greenhouse (and control), as well as rental of space in a large commercial greenhouse, where the growth of agricultural crops could be monitored. In this study, power generation data was also collected and various LSC panel designs as well as cell types were tested.

2 OPTIMIZATION LSC WINDOW

For optimization of the LSC windows, parameters tested include thickness of the acrylic waveguide, attachment methods of the LSC and PV cell, edge effect, layout, LSC enhancement per area and cell size. LSC panels were built to maximize the LSC Gain, which is heightened with higher LSC coverage, as well as maximize the Power Efficiency of the panels, which is heightened with higher cell coverage. LSC windows with different % cell coverage as well as varied design were constructed (as shown in **Fig. 2**) and tested in order to find the best compromise between Gain and Power Efficiency, resulting in the cheapest cost per Watt.

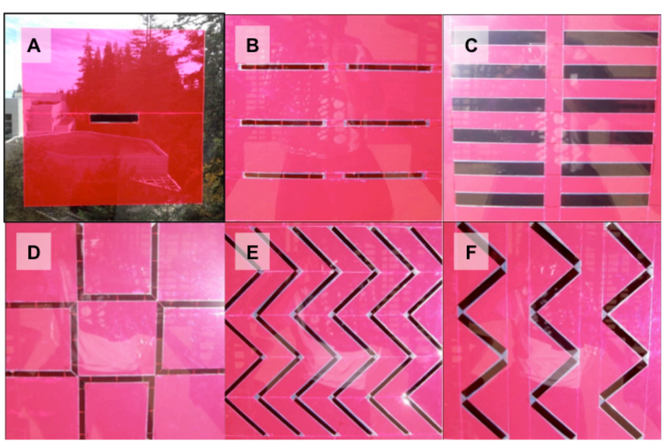

Figure 2: LSC windows of varied designs, built in order to maximize the LSC enhancement (Gain), the power efficiency, find the best compromise between the competing factors, or test different patterns. **a**: Most basic LSC window; **b**: High Gain; **c**: High Power Efficiency; **d**: Tic-Tac-Toe; **e**: Zig-Zag 1cm cell; **f**: Zig-Zag 2cm cell.

This study revealed that the cheapest cost per Watt is attained by a compromise between high LSC coverage (**Fig. 2** (**a**) and (**b**)) and that of high PV cell coverage (Fig. 2 (**c**)). The 2 cm wide Zig Zag pattern (**Fig. 2** (**f**)) yielded the lowest cost per Watt, as shown in the Table 1. The details of this study can be found in Reference 3 (Corrado et. al.).

Demo	LSC coverage	$/watt**
18% eff. PV cell	0%	$2.11
High Power Eff.	69%	$1.77
Zig Zag 1cm	85%	$1.64
Zig Zag 2cm	86%	$1.52
Tic Tac Toe*	90%	$1.65
High Gain*	95%	$2.29

*Power calculated with 0.7 fill factor in order to compare $/watt with demos using Sun Power PV cells.

**Calculated based on PV cost of $380/m^2 and LSC material cost of $10/m^2

Table 1: Cost per watt for all demos. The right-most column was calculated with $1.90/W converted to cost/m^2 for 20% efficient cells.

3 PLANT STUDIES

Experiments were performed to find the optimal concentration of dye for plant growth, as shown in **Figure 3**.

Figure 3: Testing the effect of three different concentrations of LSC dye embedded in acrylic on tomato plants in order to find the concentration most suitable for plant growth.

In order to test the effect of LSC material on plant growth, two greenhouses (10' × 24') were constructed, one LSC greenhouse and one control. In addition to this site, 6,000 ft^2 were rented inside a much larger commercial greenhouse in which half of the space was covered with the LSC and the other half was left as the control. Both sites are shown in **Fig. 4**. This site allowed for both more space for larger numbers of plants per trial as well as more uniform climate conditions. Ornamentals, cut flowers, and fruits/veggies were grown and parameters such as fresh weight, dry weight, internodal distance, number of stems, time to flower, number of flowers, number of fruit, mass of fruit, and sugar content of fruit were measured, as applicable to each type of plant. These studies are currently underway. Studies on the affect of LSCs on the growth of algae for biofuels are also being performed.

Figure 4: Study of plant response to altered light spectrum under red, electricity-generating greenhouse roof panels. **a**: UCSC Arboretum greenhouses used to demonstrate power generation as well as identify plants that respond positive/ negative to altered light spectrum; **b**: Commercial greenhouse trial used to demonstrate growth of plants in a more controlled setting with larger trial sizes.

4 CONCLUSION

LSCs can provide a lower cost per Watt of PV by their enhanced power production through additional light onto PV cells due to concentration, as well as direct incorporation into buildings without additional racking costs. Incorporation into greenhouses is a promising avenue for this technology that allows solar electricity harvesting simultaneous with agricultural crop production, thus creating a second harvest. The affect of the altered light spectrum on plants has also led to interesting results and the LSC material has been shown to enhance certain qualities of crop production. This altered spectrum plant response study is currently in progress and the results will be coming soon.

5 REFERENCES

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