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Thermal-Structural and Optical Optimization of a Crop-Waste-Derived Luminescent Solar Window for Building-Integrated Renewable Energy Generation

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Abstract - Building-integrated photovoltaic (BIPV) systems turn building facades into distributed electricity generation sites. A promising approach for creating semi-transparent solar windows is luminescent solar concentrator (LSC) technology, in which a luminescent material absorbs incoming solar energy and re-emits it. Some of the re-emitted photons are guided along a transparent waveguide to PV cells located around the perimeter of the window. Several factors limit the practical application of LSCs, including loss of optical efficiency, the trade-off between transparency and electrical output, degradation of materials, and difficulties in scaling up laboratory-scale prototypes to window-size modules. This paper presents a design and validation framework for an LSC window that uses luminescent carbon dots derived from an agricultural by-product (rice husk), dispersed in a transparent host (PMMA or glass) with edge-mounted PV cells. The framework couples (i) material synthesis and characterization, (ii) controlled fabrication of test panels at several luminophore concentrations, (iii) optical, electrical and thermal measurement with explicit area conventions, (iv) transient thermal and finite-element thermoelastic models, and (v) multi-objective optimization of power conversion efficiency against average visible transmittance under thermal and structural constraints. The protocols, metrics and constraints are specified here; measured results are not reported and no performance is claimed.

Keywords—*luminescent solar concentrator, carbon dots, rice husk, crop-waste valorization, building-integrated photovoltaics, solar window, thermal-structural analysis, optical optimization*

I. INTRODUCTION

In the built environment, there is an emphasis on reducing the energy demand of building operation while increasing the amount of renewable energy generated on site. Traditional photovoltaic modules can be installed on roofs and façades. However, if light transmission, view out or aesthetics are important, opaque modules may not be appropriate. Building-integrated photovoltaics therefore aim to integrate the energy conversion components into the building fabric itself.

A luminescent solar concentrator generally comprises a transparent waveguide with a luminophore either doped or coated onto it. The luminophore absorbs some of the incident solar radiation and emits light at a different wavelength. Some of this emitted light undergoes total internal reflection and is directed towards photovoltaic cells at the edges. This allows a large light-harvesting area to be served by a reduced PV cell area. Furthermore, some visible light can pass through the device [1], [3].

There can be issues with absorption efficiency in LSCs. Non-radiative relaxation, re-absorption, loss due to escape cones, scattering and poor optical coupling can occur, and these issues become more significant as the size of the device increases. Richards and Howard examined the issues in scaling LSCs from laboratory-scale samples to pilot and commercial modules and discussed the potential of semi-transparent windows [1]. Mandal et al. reviewed carbon-dot-based LSCs for BIPV applications and found that the choice of luminophore, efficiency, design and commercialization remain ongoing issues [2].

Crop waste can be used to produce carbon-based materials. However, the material chosen must have good repeatability in its emission properties, good spectral overlap with the solar spectrum and photovoltaic response, good compatibility with the host, low scattering and good stability. In this work, a multi-stage design and validation process is proposed.

II. RESEARCH GAP AND OBJECTIVES

The key challenge in this research is correlating the optical properties at the material level with the performance of the integrated window. Photoluminescence in solution will not be indicative of the final LSC electrical performance because of factors including concentration-induced self-absorption, matrix interactions, re-absorption, waveguide design and edge coupling. Optoelectronic properties and solar absorption can also affect the operating temperature. In addition, thermal expansion and fixturing will affect the structural behavior.

The proposed research will use an experimental and modeling approach to overcome this challenge. This will involve (1) identifying and characterizing a luminescent material from crop-waste sources, (2) producing transparent samples with well-controlled composition and geometry, (3) measuring visible transmission, edge coupling and PV I–V characteristics, (4) developing and validating a thermal and

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structural model, and (5) establishing viable trade-offs through multi-objective optimization.

III. PROPOSED DEVICE ARCHITECTURE

A transparent substrate will be used, containing the luminophore either doped or embedded. The PV cells will be placed at the edge of the window along with the optical coupling element. An encapsulation layer can be used; however, it must not cause high losses or incompatibility. PMMA or glass can be used as the substrate. The choice of substrate will depend on the optical characteristics, refractive index, thermal properties, ease of fabrication, durability and the equipment available in the laboratory. A schematic of the device is shown in Figure 1.

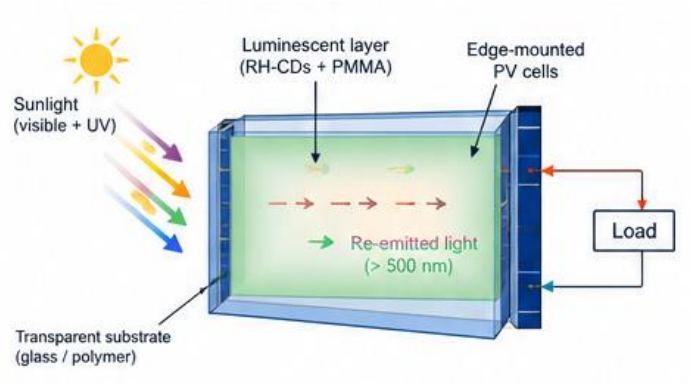


Figure 1. Schematic of the luminescent solar window. The transparent substrate contains the luminophore and the PV cells are mounted at the edges. The diagram is illustrative only and not to scale in size or performance.

Rice husk can be considered as a feedstock, as carbon-based luminescent materials have been studied using biomass sources. Once the synthesis method, yield, safety requirements, reproducibility and optical characteristics have been considered, the precursor can be chosen. A peer-reviewed synthesis method for carbon dots should be used.

IV. MATERIALS AND EXPERIMENTAL METHODOLOGY

A. Synthesis and characterization

The sample should be cleaned, dried and ground. Follow a specific synthesis route with details of the solvent, quantities of reagents, temperature of reaction, duration of reaction, purification steps and overall yield. Produce multiple samples. Basic characterization of the sample should be carried out. This should include UV-vis absorbance and photoluminescence emission. If possible, investigate the absolute PLQY, FTIR, TEM/SEM, Raman/XRD and TGA/DSC of the sample. Process the sample into a device only if it shows reproducible luminescence, good dispersibility and compatibility with the host. The synthesis pathway is summarized in Figure 2.



Figure 2. Pathway for production of composite from waste crops. Experimental validation of the process and the nature of the resultant product is required.

B. Panel fabrication and test groups

If the required equipment is available, a small sample such as a 100 × 100 mm square is best. The sample thickness should be kept consistent throughout the initial concentration screening and can be changed later. It is important to have a control sample without any doping. Multiple doped samples should be produced. Initial concentrations can be low (e.g., 0.05%, 0.10%, 0.25% and 0.50%), but these are not optimal and should be revised after considering dispersibility and optical properties.

Keep the sample dimensions, sample surface, PV cell, coupling edges, excitation and testing conditions the same. Any other important conditions should be investigated using separate samples. Repeating the measurement on the same sample provides information about the reproducibility of the instrument rather than of the sample.

C. Optical characterization

Basic optical characterization should be completed. This should include transmittance/absorbance, emission spectrum and, if possible, light output from the edges of the panel. Details of the excitation, range, slits, sample thickness, instrument calibration and testing conditions should be recorded. The average visible transmittance should be calculated over a stated wavelength range, and the weighting function used should be stated. Optical characterization will help identify whether the luminophore absorbs useful light, whether the emission spectrum overlaps with the PV response, and whether increasing the concentration and panel thickness increases scattering and re-absorption. An undoped panel should be used as a minimum control. If possible, a commercially available luminophore should also be used as a control.

D. Electrical characterization

Current–voltage (I–V) curves should be taken using a calibrated solar simulator or a documented light source. Record the irradiance, aperture, PV cell area, panel orientation, room temperature and connections. The maximum power can be calculated from the I–V curve. Keep the area the same across all comparisons, and state both the illuminated area and the total area of PV being coupled, as inconsistent area conventions can cause confusion when reporting LSC efficiency [1].

E. Thermal testing

Record the irradiance, the room temperature, and the center, edge and mid-point temperatures of the panel. This can be done using calibrated thermocouples or a properly calibrated IR technique; errors can occur with IR because of transparent and reflective surfaces. Heating and cooling curves should be recorded, and the criteria used to define quasi-steady state should be stated. A transient thermal model can be formulated as:

$$\rho c_p \, \partial T/\partial t = \nabla \cdot (k \nabla T) + Q$$

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where ρ is the density, c_p is the specific heat capacity, k is the thermal conductivity, T is the temperature and Q is the volumetric heat generation. The model should account for conduction, convection, radiation and solar absorption. Inputs should be measured where possible; otherwise, reliable material data should be used. A sensitivity analysis should be performed.

F. Structural analysis

Using finite element analysis, the displacement and stresses caused by thermal effects can be estimated. For a simple isotropic material, the thermal strain can be calculated using:

$$\varepsilon_{th} = \alpha \Delta T$$

where α is the coefficient of thermal expansion and ΔT is the change in temperature. Thermoelastic stresses must take into account both the thermal strain and the elastic properties of the material. Realistic boundary conditions should be used. The effects of changing thickness, boundary conditions, material properties and temperature gradients can be considered. This analysis will not show whether the glazing is safe; impact, weathering, fire and building codes must also be considered.

V. PERFORMANCE METRICS

The average visible transmittance is calculated as:

$$T_{vis} = \int T(\lambda) S_{vis}(\lambda) d\lambda \, / \int S_{vis}(\lambda) d\lambda$$

where $T(\lambda)$ is the transmittance and $S_{vis}(\lambda)$ is the weighting function for visible light. The maximum power is calculated as:

$$P_{max} = V_{mp} I_{mp}$$

where V_{mp} and I_{mp} are the voltage and current at the maximum power point. The power conversion efficiency is calculated as:

$$\eta_{PCE} = 100 \times P_{max} / (G \cdot A_{ap})$$

where G is the irradiance and A_{ap} is the illuminated area. This area should be stated along with the PV area and the testing conditions. The geometric gain, the ratio of areas A_{ap}/A_{PV}, may also be stated; it is not an efficiency. A_{PV} is the total area of PV being coupled. Thermal performance metrics are the maximum temperature, the average temperature, the temperature rise above room temperature, and the heating and cooling times. Structural performance metrics are the maximum displacement and the maximum stress compared with justified material limits. The overall error and uncertainty of the model should also be reported.

VI. MULTI-OBJECTIVE OPTIMIZATION

The design vector x may include luminophore concentration, panel thickness, host material and PV edge coverage. The aim is to maximize electrical output and visible transmittance while keeping the temperature, stresses and displacements within limits:

$$\text{maximize } [\eta_{PCE}(x), T_{vis}(x)]$$

$$\text{subject to } T_{max} \leq T_{allow}, \sigma_{max} \leq \sigma_{allow}, \delta_{max} \leq \delta_{allow}$$

Allowable limits should be based on material data, the application and any relevant criteria. Start with sensitivity analysis and screening design. If there are enough variables and computational resources, response surface methods or multi-objective algorithms such as NSGA-II can be used. The Pareto front should be reported so that trade-offs can be seen, and selected designs should be fabricated and tested individually to confirm the optimum.

VII. EXPECTED CONTRIBUTIONS AND LIMITATIONS

Expected contributions are (i) a reproducible method for characterizing a biomass-derived luminophore, (ii) optical, electrical, thermal and structural property data, and (iii) a range of viable designs, including a Pareto-optimal trade-off between electrical generation and daylight transmission. How much, and in which direction, performance will improve will not be known until the panels are tested. Limitations include sample variability, incompatibility with the host material, optical losses and small sample size; scaling up a small sample can be difficult. Long-term durability, fire, impact, life-cycle assessment and compliance with building codes are not part of the initial scope. Using crop waste does not by itself guarantee a reduced environmental footprint, so the chemicals used in the synthesis, the energy input, the yield and the waste streams should be reported.

VIII. CONCLUSION

This paper outlines an experimental and computational framework for the optical, thermal and structural optimization of a luminescent solar window that uses a crop by-product. The approach comprises synthesis and characterization of the material; optical, electrical and thermal testing; finite element analysis; and multi-objective optimization. The framework will be most useful if the experimental work can be replicated, correct area conventions are applied, uncertainty is quantified and claims can be verified independently.

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